

Transformer Handbook



ABB

0. FOREWORD

The objective of this Transformer Handbook is to facilitate the physical understanding, selection, ordering, operation and maintenance of the whole range of power and distribution transformers.

The target readers are personnel involved in the various stages of a transformer's service life, from planning the investment to the disposal of the transformer after use.

The handbook is arranged with the sections following the transformer's life from initial considerations and planning through ordering, installation, operation, maintenance and scrapping.

Other useful information, including more theoretical topics, is included.

Navigation through the handbook is facilitated through a three level contents list following this foreword, and the Index Section 19 page 210 at the end. Each section may be read independently of the other sections.

Some topics or phenomena are deliberately mentioned several places in the text for the purpose that readers might not read the whole content of this book from the beginning to the end, but only chapters of particular individual interest.

The first edition, Rev. 01, of this handbook issued at the end of 2003 was limited to distribution transformers and the "IEC-world".

Based on feedback from the readers and the fact that ABB has merged all transformer activities into one Business Unit, Transformers, this second edition of the handbook now covers all transformer types fulfilling the requirements of IEC and relevant ANSI/IEEE standards.

This handbook is based on ABB's knowledge and experience, and is meant to be a guide to assist the readers in handling transformer matters. ABB and the authors of the handbook cannot however be held responsible for any legal, technical or commercial use of the information herein.. No advice or information contained in this handbook shall create any warranty or binding obligation not expressly stated in an applicable written contract. Although data, technical drawings, configurations and catalogue listings are believed to be accurate at the date of publication, the readers should independently evaluate the accuracy of the information and the usefulness to their particular needs of any product or service. However, technical data are only approximate figures. Specifications for products and services are subject to change without notice.

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The standards, IEC, CENELEC and ANSI/IEEE, mentioned in the text refer to the edition given in the list of standards. For practical use only latest editions of the standards should be used.

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UK English has been selected for this document to comply with the language in IEC standards. Also the use of "." and "," in numbers follows the practice used in IEC standards. There are no real differences between the vocabulary applied in IEC and IEEE/(ANSI) standards. The only exception is the use of the words "earth"/"earthed" (according to IEC) and "ground"/"grounded" (according to IEEE).

Please also observe the Note at the end of the handbook.

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1. INTRODUCTION

In almost every place where people live and work you will find at least one transformer. But as long as it keeps working and supplying power to the escalator in the department store, the hotel lift, the office computer, the oven in the local bakery, the farm machinery or the petrochemical plant nobody gives it a second thought.

However, transformers are one of the most important units in every production process. Without them the core activities of nearly every business and factory would come to a standstill – with serious financial consequences.

After more than 100 years in the development and manufacture of transformers, ABB Transformers are well aware of this dependence. This is why we never compromise on the performance, security, quality or reliability of our products, nor on design, materials, manufacturing methods, environmental protection or recycling.

All over the world, in underground railways, in amusement parks and in every kind of factory you will find ABB transformers at work.

1.1. ABB-GROUP

ABB is a leader in power and automation technologies that enable utility and industry customers to improve performance while lowering environmental impact. The ABB Group of companies operates in around 100 countries and employs around 115,000 people (2004).

ABB Power Technologies serves electric, gas and water utilities as well as industrial and commercial customers, with a broad range of products, systems and services for power transmission, distribution and automation.

ABB Automation Technologies blends a robust product and service portfolio with end-user expertise and global presence to deliver solutions for control, motion, protection, and plant integration across the full range of process and utility industries.

As a business-to-business supplier ABB knows that value creation grows out of close relationships with customers. That means the better we know our customers' business challenges, the better we can serve them. We strengthen our relationships by building trust as a socially responsible supplier of environmentally sound products and services.

1.2. ABB Power Technologies Business Unit Transformers

ABB is among the world's leading suppliers of transformers offering a full range of products (liquid/dry), tested according to and fulfilling specified requirements in all widely applied standards, such as IEC, CENELEC, ANSI/IEEE as well as local standards.

ABB Transformers has almost 60 production facilities around the world with 13 000 employees (2004).

All of this means that with ABB Transformers you have access to a world-wide network of factories and facilities serving you locally with the most up to date technologies, providing the highest quality for standard and speciality products as well as solutions. Our warranty provides ABB quality, service and support. Our production facilities are ISO 9001/14001 certified.

ABB Transformers objective is to support you and to add value to your activities with a low total cost of ownership.

highest quality for standard and speciality products as well as solutions. Our warranty provides unified ABB quality, service and support. Our production facilities are ISO 9001/14001 certified.

ABB Distribution Transformers objective is to support you and to add value to your activities with a low total cost of ownership.

2. TRANSFORMER TYPES AND THEIR APPLICATION

2.1. POWER GENERATION, TRANSMISSION AND DISTRIBUTION

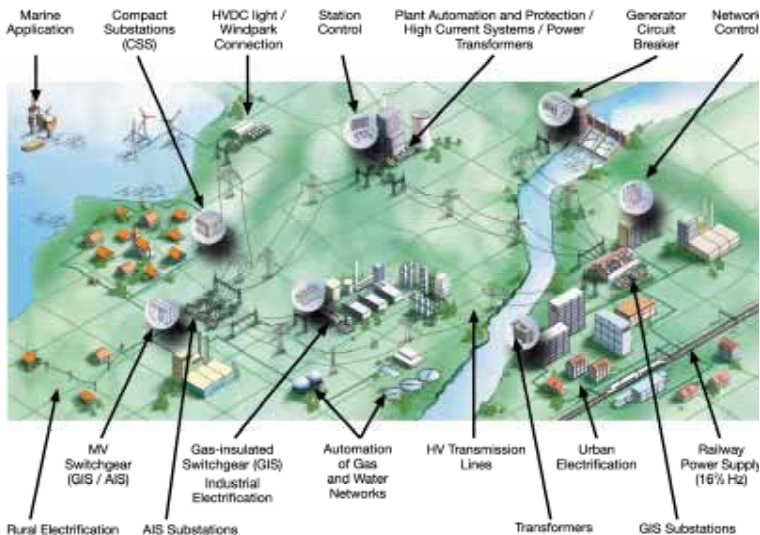
Transmission of energy is generally divided in two parts; first is transmission over long distances at high voltages, which is supported by Power Transformers. The second part is distribution of the energy from substations to the various users; this is supported by Distribution Transformers in various hierarchies.

Power and Distribution Transformers



ABB offers a full range of transformers fulfilling the requirements in IEC, CENELEC, ANSI/IEEE, other standards and customer-specific requirements.

Power transformers have primary voltages up to 800 kV. Liquid filled distribution transformers have primary voltages up to 72,5 kV and dry-type transformers with open or encapsulated windings have primary voltages up to 52 kV.



2.2. COMMON TRANSFORMER CHARACTERISTICS

In IEC Standard 60076-1 Power transformers Part 1: General, a power transformer is defined as a static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.

The same definition is found in the International Electrotechnical Vocabulary [IEV 421-01-01].

The scope of this standard includes single-phase transformers with rated power down to 1 kVA and three-phase transformers down to 5 kVA.

IEC standards do not distinguish between distribution transformers and power transformers. They are all power transformers in the sense that their purpose is to transmit power from one voltage level to another.

Traditionally, transformers that transform the voltage down to the domestic consumer voltage (usually 400 V or less) are called distribution transformers. ABB includes transformers with the highest voltage up to 72,5 kV and power rating up to a few tens of MVA in the category distribution transformers. The term power transformer is in everyday language used for transformers with higher voltage and power rating.

Common for most power transformers regardless of size and application is the basic physics and the dominant materials, like:

- special types of thin magnetic steel plates in the core, which provides the necessary strong magnetic field because of the unique magnetic properties of iron. Without iron the widely spread application of electric energy would be impossible;
- copper or aluminium as conductor materials in the windings;
- cellulose products like high density paper and pressboard as solid insulation materials has been and with few exceptions still is dominant;
- mineral oil is the dominant insulating fluid, which also has a cooling function.

In practical transformer design the manufacturer has the choice between two different basic concepts:

- core-type, see Figure 2-1
- shell-type, see Figure 2-2

The one or the other of these concepts has no influence on operational characteristics or the service reliability of the transformer, but there are essentially differences in the manufacturing process. Each manufacturer chooses the concept that he finds most convenient from a manufacturing point of view and tends to use this concept for the whole production volume.

In a nutshell we can say that while the windings of a core-type enclose the core, the core of a shell-type encloses the windings. Looking at the active part (i.e. the core with the windings) of a core type, the windings are well visible, but they hide the core limbs. Only the upper and lower yoke of the core are visible. In shell-type the core hides the major part of the windings.

Another difference is that the axis of the core-type windings is normally vertical while it can be horizontal or vertical in a shell-type.

Today much more core-type transformers than shell-type power transformers are manufactured in the world. The common transformer concept in ABB is the core-type.

Core type

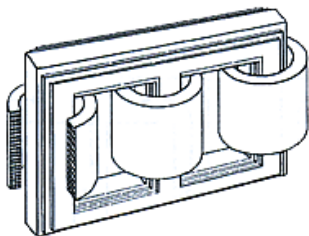


Figure 2-1

Shell type

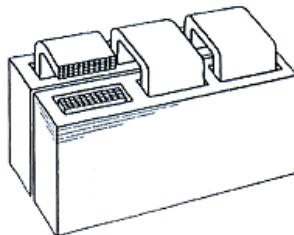


Figure 2-2

A wound type of core used in single-phase distribution transformers is shown in Figure 2-3.

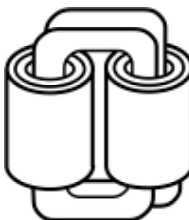


Figure 2-3

2.3. DISTRIBUTION TRANSFORMERS

2.3.1. Large distribution transformers, LDT

IEC Standard

Power range	5000 kVA and above
Primary voltage	Up to 72,5 kV
Available fluids	Mineral oil, dimethyl silicone, esters and synthetic hydrocarbons



Transformers of this type are used for receiving the energy from higher voltage levels and to transform and distribute the energy to lower voltage level substation or directly to large industrial consumers.

Transformers in this range are three phase and can be manufactured with off-circuit tap changer or on-load tap changer. Transformers provided with on-load tap changer usually have a separate tap winding.

The core is constructed of grain oriented steel laminations. The windings are made of paper insulated rectangular wire in the form of multi-layer disc or helical windings, and the conductor materials are either copper or aluminium. The tanks typically have radiators, however the smaller sizes might have corrugated tank walls.

ANSI / IEEE Standard

Substation and Unit Substation

Power range	112,5 kVA - 20 MVA
Primary voltage	Up to 69 kV
Secondary voltage	Up to 34,5 kV
Available fluids	Mineral oil, dimethyl silicone, esters and synthetic hydrocarbons



The Substation and Unit Substation Transformer are three phase and can be manufactured with off-circuit tap changer or on-load tap changer. The core is made of grain oriented silicone steel laminations. The coil is made of either aluminium or copper both in high and low voltage windings. The tank is equipped with radiators.

Substation transformers are supplied with cover mounted bushings for connection to overhead utility lines and Unit Substation transformers with wall mounted bushings on either the primary, secondary or both sides of the transformer for close connection to associated switchgear.



Padmounted transformers

Power range	75 kVA - 20 MVA
Primary voltage	Up to 46 kV
Secondary voltage	Up to 25 kV
Available fluids	Mineral oil, dimethyl silicone, esters and synthetic hydrocarbons

This type of transformers is designed for shopping centres, apartment and office buildings, schools and industrial locations etc. They can be UL (Underwriters Laboratory) listed and are used where power is needed in close proximity to the general public by commercial, industrial and utility customers.

The design provide a resistant robust construction with no externally accessible bolts, hinges, screws or fasteners providing a safe, self-contained unit that prevents entry by unauthorized personnel. Unsightly fences or other personal safety protection are not necessary.



2.3.2. Medium distribution transformers, MDT

IEC Standard

Power range	400 – 5 000 kVA
Primary voltage	Up to 36kV
Available fluids	Mineral oil, dimethyl silicone, esters and synthetic hydrocarbons.

Transformers of this type are used to step down three-phase high voltage to low voltage for energy distribution, mainly in metropolitan areas and for industrial applications.

The transformers in standard versions are three phase hermetically sealed. Flexible corrugated tank walls enable sufficient cooling of the transformer and compensate for changes in the oil volume due to temperature variations during operation.

An advantage of hermetically sealed transformers is that the oil is not in contact with the atmosphere thus avoiding absorption of moisture from the environment.

On customer request, the transformer may be equipped with oil conservator.



ANSI / IEEE Standard

Network transformer

Power range	300 kVA - 2500 kVA
Primary voltage	Up to 34.5 kV
Secondary voltage	Up to 600 V
Available fluids	Mineral oil, dimethyl silicone, esters and synthetic hydrocarbons

Networks transformers are commonly used in a grid-type secondary system in areas of high load density required for large cities. Network Transformers are designed for either subway or vault applications. Network transformers are designed for frequent or continuous underground operation.



Padmounted transformer

Power range	Up to 5000 kVA
Primary voltage	Up to 34,5 kV
Secondary voltage	Up to 4,16 kV
Available fluids	Mineral oil, dimethyl silicone, esters and synthetic hydrocarbons

This type of transformer is designed for shopping centres, apartment and office buildings, schools and industrial locations etc. They can be UL (Underwriters Laboratory) listed and are used where safe reliable power is needed in close proximity to the general public by commercial, industrial and utility customers.



The design provide a resistant construction with no externally accessible bolts, hinges, screws or fasteners providing a safe, self-contained unit that prevents entry by un-authorized personnel. Unsightly fences or other personal safety protection are not necessary.

2.3.3. Small distribution transformers, SDT

IEC Standard

Power range	Up to 315 kVA
Primary voltage	Up to 36kV
Available fluids	Mineral oil, dimethyl silicone, esters and synthetic hydrocarbons.

Transformers of this type are used to step down three-phase high voltage to low voltage for energy distribution, mainly in the countryside or low-density populated areas.

The transformers are three phase oil immersed hermetically sealed, adaptable for pole mounting or assembly in substations.

On customer request, the transformer can be equipped with an oil conservator.

Hot dip zinc coating is often the preferred surface treatment for outdoor applications.



Single Phase Polemounted

Power range	5 - 100 kVA
Voltage	Up to 36 kV
Applicable fluid	Mineral oil

Transformers of this type are generally oil immersed and suitable for pole mounting. They represent an economical option for certain networks, particularly those with low population densities. Depending on customer requirements, transformers may be connected between two phases of a three phase system (two HV bushings) or from one phase to ground (single HV bushing). They are suitable for residential overhead distribution loads, as well as light commercial or industrial loads and diversified power applications.



ANSI / IEEE Standard

Padmounted transformers

Power range	45 kVA - 150 kVA
Primary voltage	Up to 25 kV
Secondary voltage	Up to 480 V
Available fluids	Mineral oil, dimethyl silicone, esters and synthetic hydrocarbons

The Mini-Three Phase Padmounted Transformer (MTP) is designed for the needs of utility customers to reduce costs and improve aesthetics. This type is easy to handle, install and maintain. The discreet profile of the MTP is ideal for commercial applications such as banks, stores and restaurants. The MTP features a hood and removable sill instead of doors. The design allows easy access for installation and maintenance of the transformer.

The connection cables are arranged underneath the transformer.



Polemounted transformers

Power range - 1 Phase	5 kVA – 1 000 kVA
Power range - 3 Phase	30 kVA - 500 kVA
Primary voltage	Up to 36 kV
Secondary voltage	Up to 480 V
Available fluids	Mineral oil, synthetic hydrocarbons

The Polemounted distribution transformers are specifically designed for servicing residential overhead distribution loads. They are also suitable for light commercial loads, industrial lighting and diversified power applications.

The Polemounted transformers are available in both single and three phase designs. ABB also offers triplex designs for applications where large motors are the loads, e.g. for oil pumping and irrigation. "T-Connected" (Scott) three phase designs are available to serve most three-phase applications.



Single Phase Padmounted

Power range	10 kVA - 250 kVA
Primary voltage	Up to 25 kV
Secondary voltage	Up to 480 V
Available fluids	Mineral oil, dimethyl silicone, esters and synthetic hydrocarbons

The Mini-Pak is designed for cross feed (Type 2) loop feed or radial feed on a grounded wye connection, underground distribution system. It can be furnished in a complete line of ratings and in a wide range of configurations to meet the reliability, safety and operating requirements of any distribution system.



2.3.4. Dry-type distribution transformers

Dry-type transformers are used to minimize fire hazard and other environmental contamination on surroundings and people, like in large office buildings, hospitals, shopping centres and warehouses, sea going vessels, oil and gas production facilities and other sites where a fire has potential for catastrophic consequences.

ABB offers a full range of dry-type transformers with primary voltages up to 52 kV, fulfilling the requirements in IEC, CENELEC and ANSI/IEEE standards.

Application areas for both types are quite similar; however Resibloc® has an advantage in extreme climatic conditions.

2.3.4.1. Vacuum cast resin dry-type transformers

Power range	50 kVA up to 30 MVA
Primary voltage	Up to 52 kV
Climate class	C2 (IEC 60076-11)
Insulation class	220 °C (ANSI/IEEE)

Vacuum cast means that the high voltage windings are cast-in in epoxy and cured in vacuum. The high voltage windings are typically disc winding.



Typical IEC product



Typical ANSI product

2.3.4.2. *Resibloc® dry-type transformers*

Power range	30 kVA up to 40 MVA
Primary voltage	Up to 52 kV
Climate class	C2 (IEC 60076-11)
Insulation class	220 °C (ANSI/IEEE)

Resibloc® is an ABB patented process for the high voltage winding. The high voltage winding is multi layer type with a cross wound glass fibre insulation soaked in epoxy, cured in open atmosphere.



Typical IEC product



Typical ANSI product

ANSI / IEEE Standard

VPI (Vacuum pressure impregnated) and VPE (Vacuum pressure encapsulated) dry type transformers

Power range	Up to 15 MVA
Primary voltage	Up to 35 kV
Insulation class	220 Degree C

VPI transformers feature a single coat of polyester varnish and VPE transformers feature a multiple coating of silicone resin for enhanced environmental protection. They always use UL (Underwriters Laboratory) listed materials for 220°C temperature class.



VPI (Vacuum pressure impregnated)



VPE (Vacuum pressure encapsulated)

2.3.5. Other transformer types

2.3.5.1. Drives transformers

Variable Speed Drive (VSD) transformers provide the voltage transformation as well as electric isolation that is necessary for motor drives applications. Converter drives are normally fed by medium voltage networks from 5 kV up to 36 kV and the converter supply voltage usually ranges from 400 V up to 4 kV. The VSD transformer transforms the medium network voltage to the converter supply voltage. A typical application is submersible oil pump drives and similar equipment where only HV motor applications are available. VSD transformers are produced in oil insulated and dry-type configurations up to 6 MVA ratings for various types of converters and output voltages. Transformers are individually designed and manufactured according to system requirements.



2.3.5.2. Wind turbine applications

Dry-type and liquid-immersed transformers for wind turbine application are special design with low losses and small outer dimension in the transversal direction, enabling the unit to be transported through narrow door openings.

Dry-type

Power range	1000 kVA up to 2100 kVA or higher on request
Primary voltage	Up to 36 kV
Climate class	C2 (IEC 60076-11)

Special features:

- LV terminals are located at the bottom.
- No bottom frame or wheels.
- Option for a tertiary winding for auxiliaries load.



Liquid immersed

Power range	up to 4000 kVA
Primary voltage	up to 36 kV
Available fluids	Dimethyl silicone or esters

Special features:

- Hermetically sealed
- Hot-dip zinc coated and painted
- Plug-in bushings on HV side
- Protected LV bushings
- Integrated protecting device; gas, oil level, temperature, pressure



2.3.5.3. Sub sea transformers

Power rating	On request
Primary voltage	Up to 72,5 kV
Secondary voltage	1 - 12 kV
Maximum depth	2000 m
Available fluids	Mineral oil



The challenge with off-shore free flow oil production is the decreasing pressure inside the oil well. The pressure drop decreases the production lifetime of the well and the production depth.

Sub sea booster pumps makes oil production at larger depth possible caused by an artificial lift to the oil. The pumps are driven by low voltage electrical motors. The power is supplied by long HV cables from the production vessels. The main reasons for using HV supply are to reduce the weight of the cables as well as the voltage drop in the cables. Step-down transformers are installed at the sea-bed near the booster pumps.

2.3.5.4. *Underground transformers*

ANSI / IEEE Standard

Power range	75 - 1000 kVA
Voltage	Up to 30 kV
Applicable fluid	Mineral oil, esters and synthetic hydrocarbons



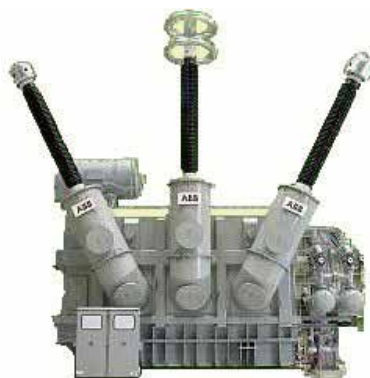
The Underground Commercial Transformer (UCT) is designed for loop feed, dead front application and is equipped with bayonet fusing or drywell current limiting fuse protection interlocked with an LBOR oil loadbreak rotary switch. There are six welded-in high voltage universal bushings wells for loop feed connection.

2.4. **POWER TRANSFORMERS**

Transformer manufacturers face several challenges in the design of large power transformers with extra high voltages (EHV) that is system voltages up to and including 800 kV.

Transient overvoltages

One of the challenges is to enable the designer to predict the transient voltage distribution within windings when transient voltages of certain shapes are applied to the transformer terminals. The voltage distribution varies, depending on a number of winding parameters. Comprehensive measurements with modern measuring equipment on a large number of windings of various types have been made in order to develop mathematical models for calculation of the voltage distribution. This development has in ABB gone on for many years with gradually decreasing deviations between calculated and measured values.



3 phase power
transformer 400 MVA

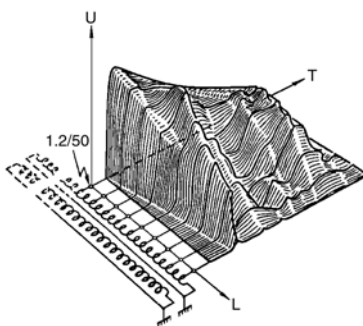


Figure 2-4

Figure 2-4 shows an example of the voltage distribution in a winding when a standard lightning impulse (with 1,2 microsecond front time and 50 microseconds time from start to the voltage has declined to half the peak value) is applied to the winding terminal. The length of the winding is indicated along the L axis, and the time along the T axis. The measured voltages to earth are indicated along the U axis.

The figure reminds one of a stony hill. Where the hill is very steep in the L direction, there are large voltage differences between points in the winding that are nearby each other.

The ability of the insulation to withstand the local dielectric stresses at numerous different spots in the winding is not only dependent on the peak value of the stress but on its duration as well. ABB has done in-depth research on basic dielectric phenomena in transformer insulation, and ABB's present competence on enabling transformers to withstand transient overvoltages is the result of several decades of work. However, the service reliability of the transformer is based on the condition that the transformer is adequately protected against transient overvoltages in compliance with good insulation co-ordination practice.

Unlike the smaller distribution transformers, which to a considerable degree are standardised, large power transformers are usually individually designed.

The magnetic leakage field

The magnetic leakage field increases with the power rating and the short circuit impedance of the transformer. For the largest transformers special precautions must be taken to ensure that the leakage field does not cause harmful heating in windings and structural parts like core clamps and tank.

Excessive heating causes gas bubbles, which represent weak points in the oil. If such bubbles rise through dielectric high-stress areas in the transformer, breakdown may occur. In addition, hot spots in contact with the oil will deteriorate the oil. For many years ABB has made comprehensive studies of the leakage field and the temperature distribution in transformers by means of thermocouples and fibre optics to obtain knowledge on how to avoid hot points that could jeopardise the service reliability of the transformers.

Mechanical forces

A third important topic is to make large power transformers able to withstand the large mechanical pulsating forces that arise during short circuit currents through the windings. Large power transformers are normally installed in systems with very high short circuit power. While thermal or economic loss considerations usually determine the current density in the winding conductors of smaller transformers, the mechanical stresses during short circuit currents often determine the winding conductor cross section in some windings of larger transformers.

The basis of ABB's design rules and manufacturing practice to achieve transformers with ability to withstand short circuit currents is theoretical considerations combined with experience from full short circuit current testing of complete transformers. More than one hundred power transformers of all sizes up to the highest power ratings manufactured by ABB have been subject to such testing.

A comprehensive treatise on mechanical forces in transformers during short circuit conditions is given in [6] 17.2 page 200.

All in all, this illustrates that to design and manufacture reliable large power transformers for high voltages in an economical and competitive way requires considerable resources and long experience.

ABB manufactures large power transformers for system voltages up to and including 800 kV and with the highest power ratings demanded by the market.

Even a transformer for a UHV test line of 1785 kV system voltage has been delivered.

Power rating limitations

When transporting the transformer from the factory to the site limitations in the transport profile might be encountered, which restrict the power rating of the transformer. The transformer height is often the limiting dimension. In that case the transformer designer has the possibility to reduce the height by choosing a 5-limb core instead of a 3-limb core. See section 6.1 page 77.

2.4.1. Generator step up transformers

These transformers take the voltage from the generator voltage level up to the transmission voltage level, which may go up to 800 kV system voltage. Such transformers are usually Ynd-connected. There are several reasons for connecting the low voltage winding in delta instead of star:

- the delta-connected winding keeps the zero sequence impedance of the transformer reasonably low;
- for large transformers the line current on the low voltage side is very high. In a delta-connected winding the current through the winding is equal to the line current divided by $\sqrt{3}$, which makes the winding work in the factory easier with a correspondingly smaller bundle of winding conductors.

The high voltage neutral is in most cases solidly earthed and the insulation in the high voltage winding is graded, that is, the insulation level in the neutral is lower than in the phase end of the winding.

Full utilisation of the generator's ability to supply active power to the system, and in addition, its ability to supply reactive power to the system and absorb reactive power from the system, requires that four transformer characteristics should be selected on the base of a thorough study. These four characteristics are:

- The short circuit impedance of the transformer;
- The secondary (high) voltage rating;
- The transformer MVA rating;
- The primary (low) voltage rating.

IEEE C57.116 – 1989TM, IEEE guide for Transformers Directly Connected to Generators describes an analysis method for selection of these characteristics.

In order to ensure that the transformer does not restrict the exchange of reactive power between the generator and the power system it may be necessary to provide tapplings in the high voltage winding of the transformer. These tapplings are normally placed at the neutral end of the winding.

In underground hydro power stations the circuit breaker on the high voltage side is often located at a distance of several hundred metres from the transformer. The transformer and the circuit breaker are connected to each other by means of a cable. When energising the transformer from the high voltage side, high frequency oscillations arise on the terminals due to travelling waves that are reflected back and forth in the cable. See [1] Section 17.2 page 200.

Every transformer winding has a number of resonance frequencies, which can be identified by means of measurements in the factory. At some of these frequencies high internal overvoltages may arise if the frequency of the oscillations that occur during energisation coincide with one of the critical resonance frequencies of the transformer winding. This potentially dangerous situation can be avoided by energising the transformer from the generator side and then synchronising the generator with the system by means of the circuit breaker at the high voltage side.

There may be a fixed connection between the transformer and the generator, or a circuit breaker may be situated in between.

When there is a fixed electrical connection, the generator and the transformer are inseparable and act as one unit. In case of failure on either side of the transformer, relays may quickly trigger the circuit breaker on the high voltage side of the transformer to disconnect the unit from the system. This sudden load rejection may cause higher voltage on the generator terminals and consequently to overexcitation of the transformer. The magnitude and duration of this overexcitation depend of the characteristics of the generator and its excitation system. The purchaser should inform the transformer supplier about the maximum magnitude and duration of this temporary overvoltage as early as possible in the project process and in any case in due time before the design of the transformer is finally determined.

Overvoltage protection of the low voltage winding of generator step-up transformers needs special consideration because of the often large difference in voltage and consequently insulation level on the two sides and the magnitude of transferred transient and temporary overvoltages from the high voltage to the low voltage side.

It is recommended that surge arresters be installed between each low voltage terminal and earth and also between terminals of different phases and, in addition, capacitors between phase terminals and earth. Typical capacitance that has been used is 0,25 μF .

The transferred overvoltages can be especially critical when the low voltage winding is disconnected from the generator.

In several cases bus ducts enclose each phase conductor between the transformer and the generator in order to minimise the risk of short circuits between the phase conductors. For large generator step-up transformers the current in these conductors are very high with accompanying strong magnetic fields, which may cause unanticipated circulating currents in transformer tanks and covers, bushings and in the bus ducts themselves. The losses caused by these unanticipated currents result in overheating if corrective measures are not included in the design. The overheating of the transformer components depends upon the method of terminating the bus ducts at the transformer end. In order to mitigate the heating problem it is suggested that design coordination meetings be arranged between the bus duct supplier, the transformer manufacturer and the purchaser prior to the design of the bus duct.



Figure 2-5

Figure 2-5 shows an example of a large three-phase generator step up transformer. The rated power is 1100 MVA and the voltage ratio 345/19 kV. In this case the transformer is made as a shell-type.

2.4.2. Step-down transformers

Step-down transformers take the voltage down from the transmission voltage to an appropriate distribution voltage. The power rating of step-down transformers may range up to power rating of the transmission line. They frequently are equipped to vary the turn ratio $\pm 15\%$ in steps of 1-1,5% by means of an on-load tap changer. (See section 7.3.2 page 100).

The electricity supply system often has several different distribution voltage levels as the supply system branches out before the voltage is finally taken down to the domestic consumption voltage level, see 2.1 page 7.

Between these different distribution voltage levels there are step-down transformers with decreasing power rating as the system approaches the consumer. They are mostly regulating transformers, and their turn ratio is often controlled by means of voltage regulation relays in order to keep the output voltage constant. However, in mesh networks with relatively strong systems on both sides of the transformer changing the turn ratio of the transformer may not essentially change the voltage, only influence the exchange of reactive power between the two sides of the transformer. Experience shows that the voltage regulation relay in such situations sends the on-load tap changer to its end position without any noticeable change in the voltage on the secondary side of the transformer.

2.4.3. System intertie transformers

System intertie transformers connect transmission systems with different voltages together with the purpose that active as well as reactive power can be exchanged between the systems.

The power rating of such transformers may be quite high, for example 1000 MVA, and they are sometimes made auto-connected in order facilitate the transport from the factory to the site by the lower weight and physical dimensions. In addition the manufacturing cost will be lower compared to a transformer with separate windings.

The turn ratio of such transformers is sometimes fixed, while tappings may be provided in other cases. The different tappings may not noticeably influence the voltage on either side of the transformer. However, the tappings provide the ability to influence the exchange of reactive power between the systems.

The insulation of the windings is normally graded. In separate windings transformers tapplings are placed in the neutral end of one of the windings. In auto-connected transformers tapplings are typically located in the phases of the low voltage side. See Figure 2-6.

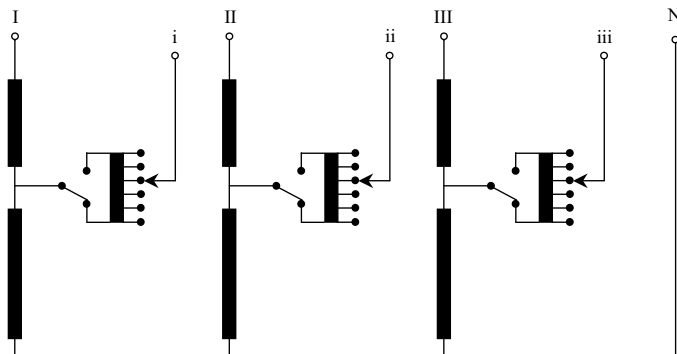


Figure 2-6

The tapplings are sometimes located at the neutral point of auto-connected transformers where the voltage level to earth and the voltage differences between phases are lower than when the tapplings are situated at the auto tap. A simpler and cheaper tap changer can then be used. On the other hand tapplings at the neutral will need a larger number of turns in the tapping range to achieve the same variation in the turn ratio as when the tapplings are situated at the auto tap or at the high voltage terminal.

The two main windings in an auto-connected transformer (or simply autotransformer) are called the common winding and the series winding. The common winding is connected to the neutral and, as the name indicates, the turns of this winding are common for both sides of the transformer. The series winding is connected at one end to the common winding and at the other end to the high voltage terminal.

The high voltage current flows through the series winding. The current flowing in the common winding is the difference between the low voltage and the high voltage current. The current in the common winding flows in the opposite direction to the current in the series winding.

The common winding and the series winding are arranged as concentric cylindrical shells, and the ampere-turns in the two windings are equal in value and opposite in direction.

The advantage of an autotransformer compared to a transformer with separate windings is that the autotransformer requires less material and consequently has smaller total dimensions, lower mass, lower manufacturing costs and lower losses.

The equivalent separate two winding power rating of an autotransformer indicates the magnitude of savings and is given by the following equation:

$$S_e = S_r \cdot \frac{U_{rHV} - U_{rLV}}{U_{rHV}} \quad (2.4.3.1)$$

The terms in this equation are the following:

S_e is the equivalent separate two winding power rating of the transformer

S_r is the power rating of the transformer

U_{rHV} is the rated high voltage of the transformer

U_{rLV} is the rated low voltage of the transformer

Equation (2.4.3.1) states that the equivalent separate two winding power rating is proportional to the difference between the rated high voltage and the rated low voltage of the transformer. The transformer mass, total dimensions, manufacturing cost and the losses are not directly proportional to the equivalent separate two winding power rating, but all these properties show a decreasing trend with decreasing equivalent separate two winding power rating.

The smaller the difference is between the high and the low voltage, the smaller will be S_e and the larger the saving in making the transformer auto-connected instead of a separate winding transformer.

Also the short circuit impedance of the transformer shows a decreasing trend with decreasing difference between the high and the low voltage. When this voltage difference is very small, the short circuit impedance of the transformer becomes also small, which makes the voltage drop in the transformer low. This is an advantage.

On the other hand, the low short circuit impedance in the transformer may make the short circuit current of the system so high that the mechanical forces in the transformer exceed its withstand ability. A solution to this problem could be to install current limiting reactors in series with the autoconnected transformer.

Another drawback of autotransformers is that due to the metallic connection between the circuits on both sides of the transformer a disturbance in one of the circuits also involves the other circuit. If for example a single-phase earth fault occurs in one of the circuits, voltage rise to earth on the healthy phases will occur in both circuits. If the earth fault occurs in the circuit having the highest voltage, the voltage rise to earth on the healthy phases of the low voltage circuit may become very high, dependant on the difference in system voltage of the two circuits. Direct earthing of the neutral will mitigate this phenomenon.

One of the commonest applications of the auto connection is in large high voltage system intertie transformers where the system neutral is directly earthed. These transformers are often very large units with 5-limb cores. A tertiary d-connected winding is normally included to provide low zero sequence impedance and triple harmonic magnetising currents to avoid triple harmonics in the magnetic flux and in the induced voltages. If the tertiary winding is not intended for connection to any power system, one corner of the winding should be solidly earthed to fix the potential of the winding.

It is important that such autotransformers are protected against transient overvoltages on both sides by means of surge arresters between phases and earth.

Within certain geographic areas system voltages on several different voltage levels may exist, often mainly of historical reasons, and there is often a need to connect these systems together by means of transformers. Due to the large dependence on electric power in the modern society spare transformers for these system connection points are needed.

In order to avoid a large number of spare transformers, each with one specific voltage ratio suitable for use at a particular connection point in the power system, a spare transformer with several different voltage ratios can be made. Such a transformer will then be applicable at several different connection points.

An example of connection diagram for such a transformer is shown in Figure 2-7. The transformer is YN-auto-connected with an on-load tap changer in the neutral. The low voltage terminal can be connected to one of several tapplings in off-circuit condition. In this way the following voltage ratios are achieved: 400kV to 230kV, 400kV to 132kV, 400kV to 110kV, 230kV to 132kV and 230kV to 107kV. By means of the on-load tap changer the turn ratio can be adjusted some percents up or down, varying somewhat with the particular system voltages the transformer is used for. The maximum power rating is 450 MVA at voltage ratio 400/230 kV. At other voltage ratios the power rating is in the range 325 to 200 MVA, dependent on the voltage ratio used.

The transformer has also a delta-connected tertiary winding which limits the zero sequence impedance of the transformer to a reasonably low value. The voltage and power rating of the tertiary winding is dependent on the voltage applied at the high voltage terminal, 400 or 230 kV.

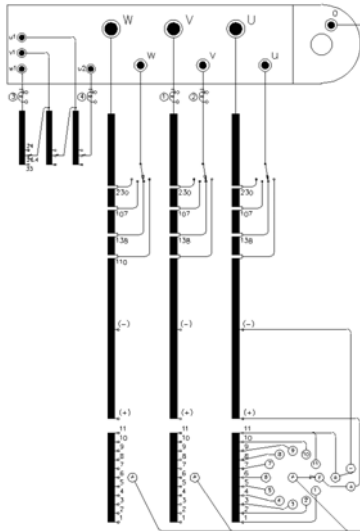


Figure 2-7

Figure 2-8 shows a picture of the transformer, which is made as a shell-type.



450 MVA auto-connected system intertie transformer

Figure 2-8

2.4.3.1. Phase-shifting transformers

A phase-shifting transformer is a special type of system intertie transformers. It provides the possibility to insert a voltage with an arbitrary phase angle in the power system. This is used for two main purposes:

- To control the power flow between two large independent power systems;
- To balance the loading when power systems are connected together in more than one point so that loops exist and the impedances in parallel paths results in undesired distribution of power flow in the paths.



We can illustrate this by means of examples.

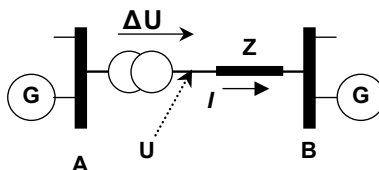


Figure 2-9

A and B in Figure 2-9 are two strong power systems connected by a line with impedance Z . To transmit active power from system A to system B the voltage to the left of Z , U , must be leading in relation to the voltage to the right of Z . To make the principle illustration simple, the real part of Z is neglected and the power factor at B is assumed to be 1. The transformer is a phase-shifting transformer, inserting a voltage ΔU in series with the impedance Z . The transformer is considered to be ideal, that is, the transformer impedance is neglected.

The voltages at A and B are approximately equal, $U_A \approx U_B$. ΔU is adjusted so that:

$$\Delta U - I \cdot Z = 0$$

The following vector diagram applies:

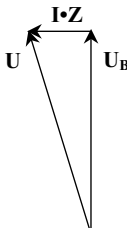


Figure 2-10

In another example there are two power systems that are linked together in two points. The power flow goes then in two branches with impedances Z_A and Z_B . The value of the two impedances determines the distribution of power flow through the two branches. This distribution may not comply with the desired distribution.

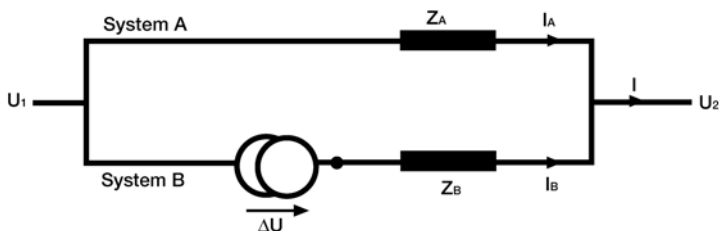


Figure 2-11

By means of a phase-shifting transformer a voltage ΔU is inserted in system B, which increases the current I_B and decreases I_A at a given total load current I . We will illustrate this by means of a numerical example.

Assume the difference between Z_A and Z_B is quite large, say $Z_A = 30\Omega$ and $Z_B = 300\Omega$, that is the relation 1:10. For the sake of simplicity in the demonstration of the principle effect of the use of a phase-shifting transformer the real part of Z_A and Z_B is neglected. Assume further that the system voltage is 800 kV and that the total power that is transmitted from the left to the right side in the figure is 1000 MVA. The total current I is then 722 A. Let us first assume that $\Delta U = 0$, in other words there is no phase-shifting transformer in system B. Simple calculations show that $I_A = 656$ A and $I_B = 66$ A, which is 9 and 91% of the total load current respectively.

Let the desired load current distribution be for example 50% of the total current in each of the two systems A and B. 361 A causes a voltage drop of 10 830 V across Z_A and 108 300 V across Z_B . An additional voltage ΔU inserted in system B to increase the current through Z_B from 66 to 361 A must then compensate the difference of 97 470 V between the two voltage drops. A phase-shifting transformer can provide this additional voltage.

Assume that the power factor of the load current I is 1. The following vector relationships exist before and after the insertion of ΔU , see Figure 2-12.

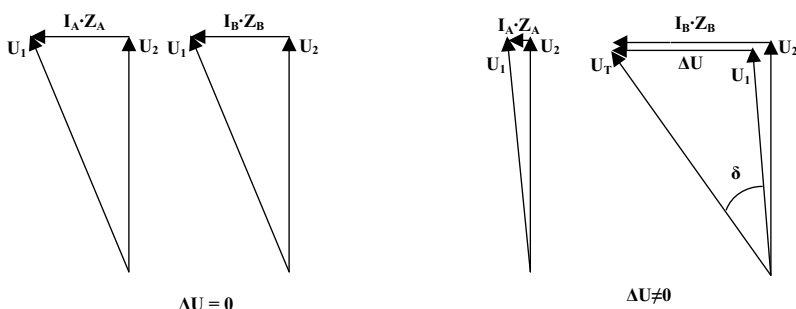


Figure 2-12

To achieve ΔU the phase-shifting transformer must at its secondary terminal provide a voltage U_T , which is higher than the primary voltage U_1 and, in addition, displaced an angle δ in the positive direction in relation to U_1 (the positive direction defined counter-clockwise). δ can be calculated from the vector diagram to the right and is in this case $11,9^\circ$.

If the total load current is only the half of 722A and the 50/50% distribution between system A and B still is desired, the voltage drops across Z_A and Z_B becomes only the half of those in the last example. The need for additional voltage to drive the desired current through Z_B will then also be only the half, that is $0,5 \cdot 97\,470\text{ V} = 48\,735\text{ V}$. The displacement angle δ becomes now 6° .

If Z_B had been smaller than Z_A , the direction of ΔU must be the opposite to prevent that the current I_B would be too high in relation to the desired load distribution.

Also the power factor ($\cos \varphi$) of the load current I influences the required displacement angle.

In the preceding the impedance of the phase-shifting transformer has been ignored. In reality the transformer impedance will add to the system impedance and may cause need for a larger angle displacement.

It should be noted that the phase-shifting transformer has an impact on the exchange of both active and reactive power between systems or branches of systems.

To fulfil the user's intentions the phase-shifting transformer must be able to vary the displacement angle in appropriate steps within a certain range.

The basic way to provide variable angle displacement (phase-shifting) between the primary and secondary voltage in a transformer is to connect the winding of one limb in a three-phase transformer in series with a winding situated on one of the other limbs.

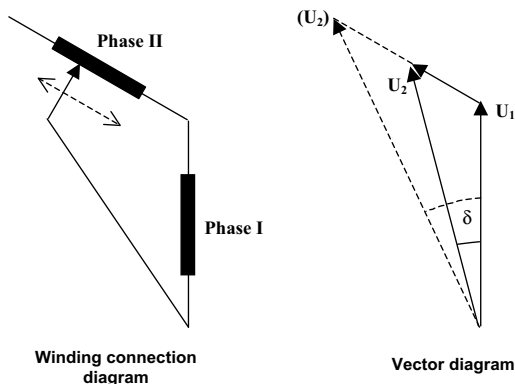


Figure 2-13

The angle displacement can be obtained in principle achieved by means of a single core three phase transformer. However, the application of phase-shifting transformers is mainly in systems with very high voltage, and the throughput power rating is quite large. In order to fit voltage and current to available tap-changers, it may be necessary to use two separate transformers, one magnetising transformer and one booster transformer. In the circuit where the tap-changer is located the voltage can be chosen independently of the service voltage of the power system.



Figure 2-14

Figure 2-14 shows a principal diagram of how the magnetising transformer and the booster transformer are connected together. The tap-changer is typically located at the secondary side of the magnetising transformer.

A more detailed three-phase connection diagram is shown in Figure 2-15. A voltage, which can be varied in size, from the secondary side of the magnetising transformer is applied to a different phase of the primary side of the booster transformer. The voltage transferred to the secondary (high) voltage side of the booster transformer will then be displaced an angle $2\pi/3$ in relation to the source side voltage. By varying the size of the voltage inserted by the booster transformer, a variable angle δ is achieved between the voltage on the source side and the total voltage on the load side of the phase shifting transformer, which is the vectorial sum of the voltage on the source side and the $2\pi/3$ displaced voltage provided by the booster transformer.

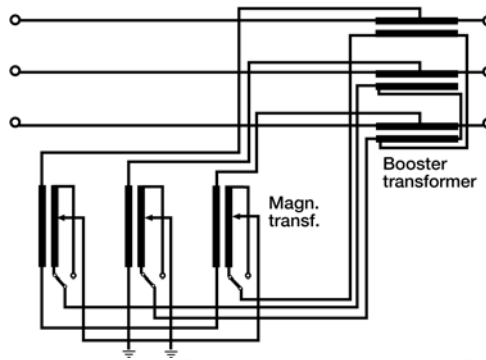


Figure 2-15

The arrangement with magnetising and booster transformer can also be made in many other different ways.

The phase displacement requires a certain apparent power, which Figure 2-16 illustrates.

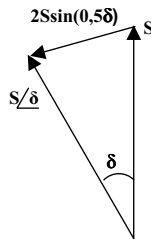


Figure 2-16

From the diagram it appears that $S_\delta = 2 \cdot S \cdot \sin(0,5\delta)$, where S_δ is the phase-shifting power and S the apparent throughput power. The magnetising transformer as well as the booster transformer must be rated for the maximum phase-shifting power.

Is for example the maximum angle $\delta = 30^\circ$ and the rated apparent throughput power rating 1000 MVA, the rating of the magnetising and the booster transformer will be 520 MVA each ($1000 \cdot 2 \cdot \sin(30/2) = 520$). The service voltage is in most cases also high.

In other words, the units are quite large. Because of transport limitations the two transformers are usually placed in separate tanks.

Regarding differential relay protection of phase-shifting transformers it should be noted that a considerable phase angle difference between the source and the load current causes a much higher normal current difference than in ordinary power transformers, so a special differential scheme is required.

A short-circuit in the circuit between the magnetising and booster transformer would be very harmful to the transformers, and it is recommended that bus ducts are provided around the conductors connecting the secondary side of the magnetising transformer and to the primary side of the booster transformer.

In phase-shifting transformers with magnetising and booster transformer (two-core design) there is a dielectric design question that needs special attention. If a transient voltage occurs at either side of the series winding of the booster transformer, the connected winding of the magnetising transformer will also be exposed to a high voltage, and high frequency oscillations may arise on the leads connecting the two transformers. More comprehensive mathematical models may be required to calculate the transient voltage distribution in this configuration than in a single core transformer.

A dialogue between the purchaser and the supplier regarding the overvoltage protection is recommended.

Information to be provided by the purchaser at enquiry

In addition to the information needed regarding ordinary power transformers, is first of all the desired total angle displacement range. The displacement range should primarily be specified in no load condition. However, the purchaser must ascertain that the range is sufficiently large also under relevant load conditions because the impedance of the transformer, which may vary considerably over the regulating range in phase-shifting transformers, makes the displacement range smaller than in no load condition. So the purchaser should then specify the desired displacement range under specific load conditions, or alternatively state acceptable ranges for the transformer impedance.

Further the purchaser should provide information to the supplier regarding

- the power system where the transformer is going to operate
- the purpose of the transformer
- the switching arrangements to be used to take the transformer in and out of operation
- whether a by-pass switch will be installed
- whether the transformer will operate in series with series capacitor banks
- whether the transformer will operate with two or more other phase-shifting transformers in parallel or in series

The above list of items should not be considered as exhaustive.

Reference is also made to IEEE Std C57.135-2001TM IEEE Guide for the Application, Specification, and Testing of Phase-Shifting Transformers. A revision of this standard might take place in a co-operation between IEC and IEEE with the purpose to issue a new edition of the standard, which is approved by both organisations and with an IEC-IEEE dual logo.

2.4.3.2. HVDC transformers

HVDC means High Voltage Direct Current. The first HVDC transmission line was established in Sweden in 1954. Since then many HVDC transmission systems have been installed around the world. ABB has delivered more than half of the converter stations, which are key components.

HVDC transmission is sometimes an economical and technically advantageous alternative to ac transmission. That applies particularly when large bulks of power are transmitted over long distances by overhead line or under the sea by means of submarine cable.

The basic diagram for a HVDC transmission is shown in Figure 2-17.

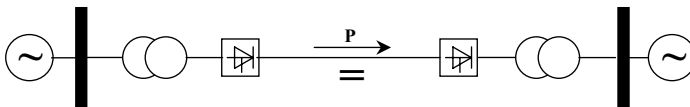


Figure 2-17

An HVDC transmission has a converter station at each end of the line or cable. The main components of the converter stations are the transformers and the valves. The alternating voltage of a supply system is transformed to a voltage level suiting the converter rectifier to transmit the intended power. It is then rectified in a converter arrangement with controlled valves consisting of many thyristors semi conductors. At the receiving end of the line or cable there is another converter station. This is operated as an inverter that converts the direct current back to alternating current, which then is transformed to the voltage of the network being supplied. The direction of power flow can easily be changed without interruption in the operation.

Compared to ac transmission lines dc lines can operate with narrower corridors. Large areas of farmland or forests may then be saved. Further, stability aspects do not limit the power transmission capability of the line.

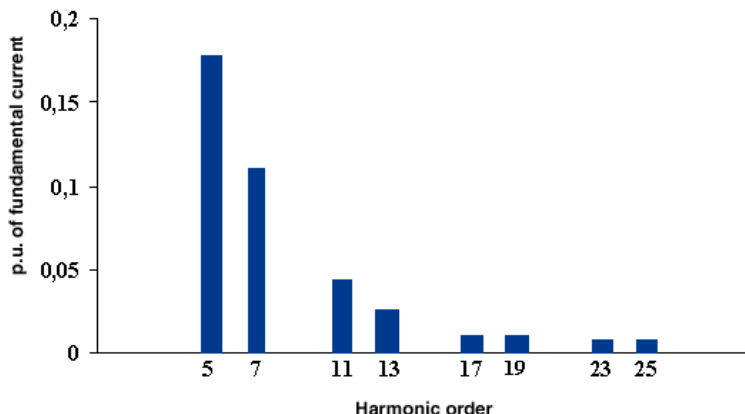
For a given quantity of conductor material in the line the losses in a dc line are lower than the losses in an ac line.

By means of HVDC non-synchronous ac systems can be linked together. The transformers provide that there are no galvanic contacts between the dc equipment and the ac systems. This prevents the direct current from entering the ac systems.

The currents flowing through the windings of converter transformers contain certain harmonics whose magnitudes depend of the parameters of the converter station. The method to determine the transformer load losses is based upon two load loss measurements, certain assumptions and a specific calculation scheme. See section 7.4 and 10.3 of IEC 61378-2.

The transformer supplier shall calculate the value of the actual service load loss based on a given harmonic spectrum for the load current. The purchaser shall provide this spectrum.

Figure 2-18 shows an example of a harmonic current spectrum of a 6-pulse connection.



Example on harmonic current spectrum in p.u. of the fundamental frequency current in a 6-pulse connection

Figure 2-18

Figure 2-18 shows that the 5th and 7th harmonics are the largest. Higher harmonics decrease with increasing harmonic number.

6-pulse connection means that there are 6 pulses in the direct voltage per period of the fundamental ac voltage, as shown in Figure 2-19 below.

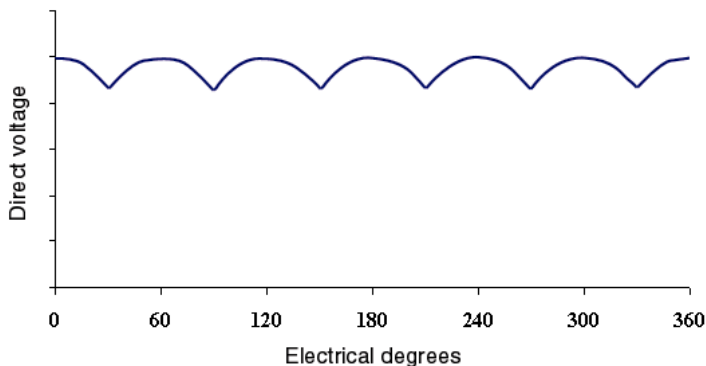


Figure 2-19

Figure 2-19 shows how the direct voltage varies during one period of the ac system voltage. The direct voltage consists of 6 pulses during one period. It is not an ideal straight line, the pulses appear as a ripple on the direct voltage.

The ripple can be reduced by combining two 6-pulse valve bridges to a 12-pulse connection as shown in Figure 2-20. Then the 5th and the 7th harmonics disappear from the current supplied from the ac network. However, the 5th and 7th harmonics still circulate between the two transformers of the 12-pulse group and may give considerable contributions to the total load losses in the transformers. The 5th harmonic may amount to nearly 20% of the fundamental frequency current.

In the station where the dc current is converted to an ac current, the current can in principle be converted to any frequency. The frequency can be given by the ac system itself or by a separate synchronous machine. So an HVDC-link is suitable for connecting together ac systems with different frequencies, for example 50 and 60 Hz.

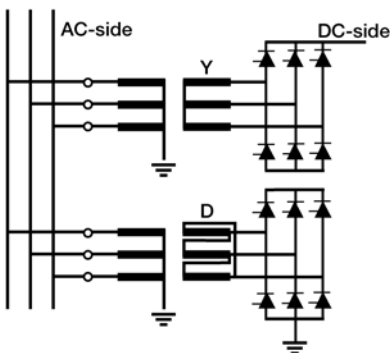


Figure 2-20

The voltages at the valve sides of the two transformers in Figure 2-20 are displaced 30 electrical degrees in relation to each other by connecting one of the windings in star and the other one in delta. Notice that the phase-to-phase voltages of the two transformers are the same on the valve side as well as on the ac network side.

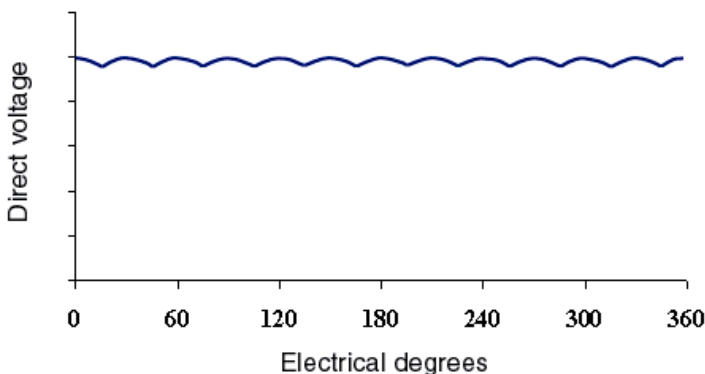


Figure 2-21

Figure 2-21 illustrates the reduced ripple on the direct voltage of a 12-pulse connection compared to the 6-pulse connection in Figure 2-19.

The relation between the ideal dc-voltage across the two bridges in Figure 2-20 and the phase-to-phase voltage on the valve side of the transformers can in no load condition be written as:

$$U_D = \frac{6 \cdot \sqrt{3}}{\pi} U_{ac} \cdot \cos \alpha \quad (2-1)$$

In this equation

U_D is the dc voltage across the two series-connected valve bridges in Figure 2-20

U_{ac} is the phase-to-phase voltage on the valve side of the transformer

α is the valve delay angle (control angle)

For $\alpha = 0$ the voltage U_D becomes $2,7U_{ac}$. In loaded condition voltage drop in the transformer and the valves reduces the conversion factor from 2,7 to the range 2,4 – 2,5 normally.

The losses in a converter bridge are around half a percent of the throughput power while the inductive drop is 5 – 10%.

The valve-side winding for the lower bridge (the bridge closest to earth) in Figure 2-20 is exposed to a dc-potential of around one fourth of the dc-line potential and the valve-side winding for the upper bridge of three fourth of the same potential.

The voltage distribution between solid and fluid transformer insulation is capacitive when exposed to ac. This means that the voltage distribution and dielectric stresses are determined by the permittivity of the materials.

In contrast when exposed to dc-potential the voltage distribution and dielectric stresses are determined by the resistivity of the materials. The insulation materials are basically the same, mineral oil and cellulose products. Because the resistivity of the solid insulation materials is considerably higher than the resistivity of the transformer oil, almost all the dc-voltage lies across the solid insulation. Consequently HVDC transformers contain a much higher share of solid insulation than in ac transformers, around three times as much.

Transmission systems with dc voltages up to ± 600 kV are in operation. To demonstrate the ability to withstand dc voltage the valve windings of HVDC transformers are in the delivery test subject to:

- dc separate source voltage withstand test. See section 8.2.3 and 10.4.3 of IEC 61378-2;
- polarity reversal test. See section 8.2.4 and 10.4.4 of IEC 61378-2.

To control the service voltage HVDC transformers are equipped with a fairly large tapping range on the line side. Further there is a need for strict control of the short circuit impedance of the transformers. The deviation in impedance between individual phases must be kept small.

IEC 61378-2 specifies that the impedance variation at the principal tapping and the variation of the impedance over the tapping range for transformers of duplicate or similar design for the purpose of identical application in service or interchange ability shall not exceed $\pm 3\%$ of the mean test values.

The reason for this requirement is to a great extent the need for efficient cancelling of harmonics in a 12-pulse bridge connection. Large variations between phases, units and star and delta connected windings will increase the size of the filters.

Alternatively to the transformers shown in Figure 2-20 with two 3-phase transformers, one with delta and one with star connected winding at the valve side, three single-phase transformers could be used. In that case each transformer has two valve-side windings, one for d-connection and one for y-connection in a bank with the two other single-phase transformers.

If a spare transformer is desired, the single-phase transformer solution has the advantage that just one single-phase transformer can cover the need. The choice of solution, 3-phase or single-phase transformers may also depend on restrictions in unit dimensions and weight.

The modern high voltage and high capacity converter is a sophisticated product requiring experience and high skill in design and specific quality control in production.

2.4.4. Industrial transformers

2.4.4.1. Furnace transformers

Transformers of this type are used in the steel melting and metallurgical industry. They are characterised by high secondary current, for steel up to 90 kA and for ferroalloy up to 160 kA electrode current, and a wide secondary voltage range. The secondary voltage is normally regulated by an on-load tap changer (OLTC) located in the high voltage winding or in an intermediate circuit of a two-core design (booster regulation) within the transformer tank. Furnace transformers have secondary voltages up to 1500 V. Furnace transformers can roughly be divided into two groups:

- AC Furnaces
 - Arc furnaces
 - Reduction furnaces
 - Furnaces for special purposes
- DC Furnaces



160 MVA steel EAF Transformer.
Internal closure.

Arc furnace transformers are used for melting scrap metal. Usually in combination with an arc furnace, there is a ladle furnace. The ladle furnace is used in the process of refining the metal melted by the arc furnace. Arc furnace transformers are normally designed as three phase units.

Reduction furnace transformers are mainly used in the metallurgical industry. Production of ferro-alloys is an important application. The major alloys are ferro-silicon, silicon metal and ferro-manganese. Other significant alloys are ferro-nickel and ferro-chrome. Reduction furnaces are also used in the production of non ferrous metals such as copper, nickel, tin, lead and zinc. Reduction furnaces are also used in the production of calcium carbide. The most common design for reduction furnace transformers is single phase.

Examples on furnace transformers for special purposes can be for production of electrode material and electro slag refining, where the latter is production of very high quality steel.

AC furnace transformers are made both as single- and three-phase. In many installations around the world, furnace transformers have been designed as shell type. All other transformers for this purpose are made as core type. Manufacturing of new AC furnace transformers are made as core type with a few exceptions.

DC furnace transformers are also used to melt scrap metal (steel). Three-phase is the most common design. Since direct current is used in the melting process the transformer is installed in combination with a rectifier, which feeds the furnace.

2.4.4.2. *Convector transformers*

One of the main differences from other types of transformers is that the load currents contain higher harmonics due to the distorted waveform. The distorted current waveform is caused by the convector connected to the transformer. Currents with multiple frequencies of the net frequency flow from the convector to the transformer. This has to be considered when the transformer is designed because harmonic current leads to higher losses and temperatures in the transformer. Network regulations also require reduction of harmonic distortion.

The most common use for convector transformers is found in applications such as:

- Variable speed drives - VSD
- Aluminium electrolysis



79 MVA Rectifier Transformer.
Common tank.

Other applications can be chemical electrolysis, DC arc furnace (see section 2.4.4.1), graphitizing furnaces, traction substations (see section 2.3.5), copper refining etc.

VSD transformers are used in applications where a variable speed is required on the motor shaft. VSD are used in a wide variety of applications such as rolling mill drives, ship propulsion systems, mine hoist drives, wind tunnels drives etc. Figure 2-22 shows a basic circuit diagram for a VSD system configuration for a wind tunnel. The transformer is a 12-pulse unit that feeds two 6-pulse rectifiers, which are coupled via a dc-link containing two smoothing reactors that are connected to two inverters, which in turn is connected to a synchronous motor. The transformer is also equipped with a tertiary winding, which is connected to a filter. The purpose of the filter is to reduce the harmonic voltage distortion in the HV supply system as well as increasing the power factor of the load.



64 MVA Drives Converter
Transformer. 12 pulse

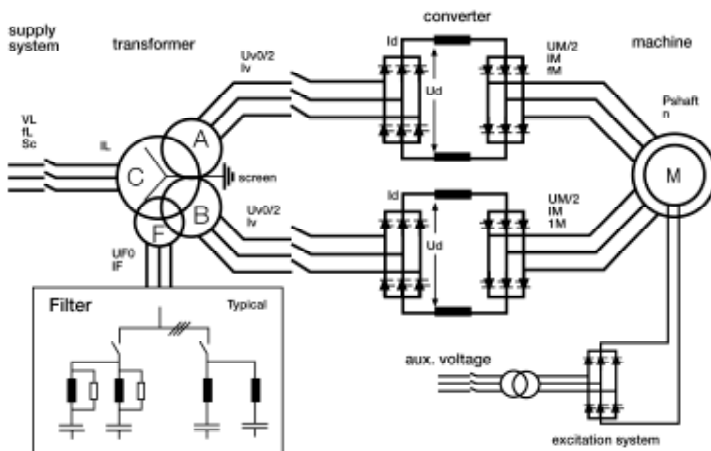


Figure 2-22

One major converter transformer application is aluminium electrolysis. Such converter transformers are characterised by high secondary currents, secondary voltages up to 1500 V and a large voltage regulating range. Due to the converter valves the currents in the transformer windings will not be sinusoidal but contain harmonics which must be considered when designing the transformer. Integrated transformer and converter units for DC currents up to more than 100 kA have been manufactured.

Usually, four, five or six converter transformers are connected in parallel to feed one aluminium pot-line. Depending on the degree of disturbance tolerated on the network and/or on the DC current output, the transformers can be connected as (6-), 12-, 24-, 36- or 48-pulse system. The disturbance on the network and on the output DC current decreases with increasing pulse number. A 12-pulse system is made by two 6-pulse systems with 30 degrees phase shift between the two systems. This is achieved by connecting one 6-pulse system in delta and the other in star (wye).

A diagram for a typical unit for this purpose is a 12-pulse transformer with phase shift winding as shown in Figure 2-23.

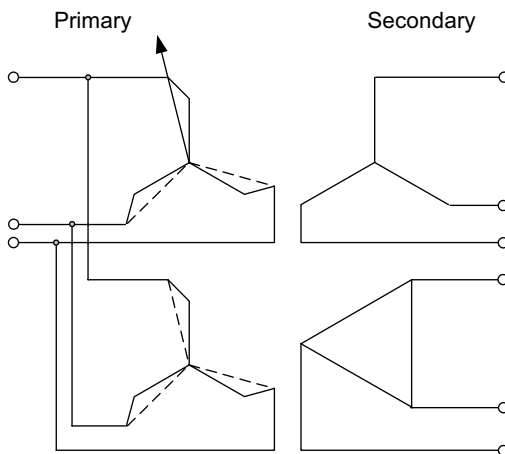


Figure 2-23

A typical aluminium pot-line is built as a 48-pulse system with four rectifier transformers connected in parallel. In this case, the system is built up by four 12-pulse units with different phase shift windings. A 48-pulse system can be achieved by the following phase shift angles, $+11,25^\circ$, $+3,75^\circ$, $-3,75^\circ$ and $-11,25^\circ$.

As mentioned, one of the characteristics of rectifier transformers for aluminium plants is a very large regulating voltage range, from zero volts up to several hundred volts. The magnitude of the secondary voltage depends on how many pots that are connected in series.

When diodes are used, it is necessary to make a separate regulating transformer equipped with on-load tap changer in series with the rectifier transformer to regulate the secondary voltage. The regulating transformer is often auto-connected. In combination with diode rectifiers, transducers are normally used to regulate the voltage between the steps of the on-load tap changer. The regulating transformer that is feeding the rectifier transformer may be built in the same tank as the rectifier transformer or it may be made as a separate unit. Another possibility to regulate the secondary voltage is to use thyristor rectifiers, which may replace the regulating transformer and the transducers. When thyristor rectifiers are used it may be sufficient to equip the rectifier transformer with an off-circuit tap changer (OCTC).

At inquiry and order the technical specification for the convertor transformer needs some additional information compared to power transformer specifications. This information should be provided by the system designer or the purchaser. Such information is valve winding current waveform, i.e. harmonic current spectrum. "The harmonic content influences the transformer losses in general but, more importantly localised winding loss and hence potential hot spot temperatures" [Draft IEC 61378-3 convertor transformers - Part 3: Application guide, Section 11.8.2].

When this information is known, the windings can be designed to avoid unacceptable temperatures. The distortion of the power system voltage caused by the harmonic current is another aspect to consider. Disturbance due the harmonic content of the currents can be reduced by increasing the pulse number, as mentioned above.

There may also be special requirements regarding tolerances on the transformer short circuit impedance because this impedance influences the efficiency of the electrolysis process.

2.4.5. Traction transformers

Traction systems can broadly be divided into two major groups, those who use alternating current (AC) and those who use direct current (DC). In Europe the following systems are found:

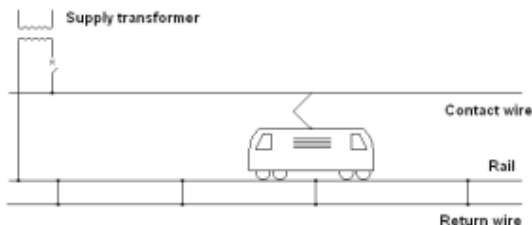
- 15 kV AC 16 2/3 Hz
- 25 kV AC 50 Hz
- 1,5 kV DC
- 3 kV DC
- 1,2 kV DC

2.4.5.1. Stationary transformers (line-feeder transformers)

Regarding stationary transformers (supply-, feeding transformers) for AC distribution there are mainly three different systems in use

1. Single phase feeding system with return conductor
2. Single phase feeding system with booster transformer
3. Two phase feeding system with auto transformer

Figure 2-24 shows system number 1, single phase feeding system with return conductor.

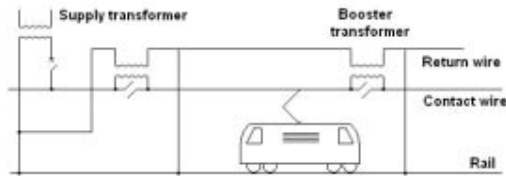


System number 1: Single phase feeding system with return conductor

Figure 2-24

This is the simplest way of feeding the trains, using only one phase connected to the contact wire, with the return current through the rails, avoiding return earth currents by means of draining transformers. This is a simple and cost effective system, but has the disadvantages of high system impedance and high losses. This system is applied in 50/(60) Hz/ 16 2/3 Hz applications and is particularly suitable for medium distance/speed routes.

Figure 2-25 shows system number 2, single phase feeding system with booster transformer.

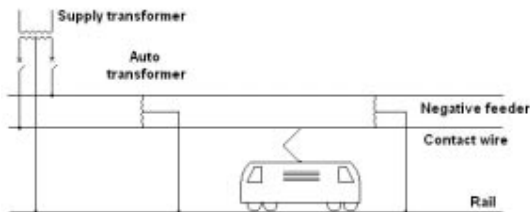


System number 2: Single phase feeding system with booster transformer

Figure 2-25

A major improvement is found in this system where a booster transformer (unity ratio) is implemented. The primary circuit is connected across a gap in the contact wire and the secondary across an insulated rail section. In linear mode (when the booster transformer is not saturated), the traction return current flowing through the secondary circuit is forced to be equal to the current flowing through the overhead line and in the primary circuit. This system is commonly used.

Figure 2-26 shows system number 3, two phase feeding system with autotransformer.



System number 3: Two phase feeding system with autotransformer

Figure 2-26

In the third system, the secondary winding of the supply transformer provide two equal voltages with 180° phase displacement by dividing the secondary winding into two equal parts. One phase is connected to the contact wire and the other phase is connected to a separate overhead line called the negative feeder. The intermediate point of the secondary winding is connected to the rail. At Auto Transformer Station (ATS) location, the winding is connected to the contact wire, the negative feeder and the rail is connected to an intermediate point of the autotransformer winding. The advantage with this system is that the spacing between feeder stations is increased. The system is extensively used in France for the French high speed train TGV. Many countries with high speed projects have adopted the concept.

In systems, where the locomotive is fed by DC current a three phase rectifier transformer is required to feed the rectifier.

2.4.5.2. Locomotive transformers

This transformer is installed on the locomotive. Factors of importance for such transformers are size and weight. To achieve low weight and volume, less material is used which in turn increases losses and temperatures in the transformer. To deal with the high temperatures, insulation which can withstand high temperatures are used, such as aramid, polyimide or polyester glass and various high temperature insulating liquids.



2.5. REACTORS

This section describes reactors for a number of different applications.

Supplementary information can be found in IEC 60076-6 Part 6: Reactors (At present in process).

2.5.1. Shunt reactors

The need for large shunt reactors appeared when long power transmission lines for system voltage 220 kV and higher were built. The characteristic parameters of a line are the series inductance (due to the magnetic field around the conductors) and the shunt capacitance (due to the electrostatic field to earth). An equivalent diagram for a line is shown in Figure 2-25.

Both the inductance and the capacitance are distributed along the length of the line. So are the series resistance and the admittance to earth.

When the line is loaded, there is a voltage drop along the line due to the series inductance and the series resistance. When the line is energised but not loaded or only loaded with a small current, there is a voltage rise along the line (the Ferranti-effect).



Shunt reactor, 400 kV, 150 MVar

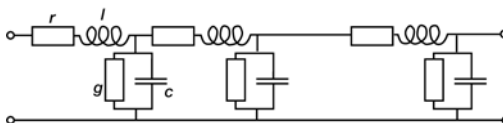


Figure 2-27

In this situation the capacitance to earth draws a current through the line, which may be capacitive. When a capacitive current flows through the line inductance there will be a voltage rise along the line.

To stabilise the line voltage the line inductance can be compensated by means of series capacitors, and the line capacitance to earth by shunt reactors. Series capacitors are placed at different places along the line while shunt reactors are often installed in the stations at the ends of line. In this way the voltage difference between the ends of the line is reduced both in amplitude and in phase angle.

Shunt reactors may also be connected to the power system at junctures where several lines meet or to tertiary windings of transformers.

Transmission cables have much higher capacitance to earth than overhead lines. Long submarine cables for system voltages of 100 kV and more need shunt reactors. The same goes for large urban networks to prevent excessive voltage rise when a high load suddenly falls out due to a failure.

Shunt reactors for system voltages up to 765 kV have now been in service for several tens of years. At present still more shunt reactors are being installed.

Shunt reactors contain the same components as power transformers, like windings, core, tank, bushings and insulating oil and are suitable for manufacturing in transformer factories. The main difference is the reactor core limbs, which have non-magnetic gaps inserted between packets of core steel.

Figure 2-28 shows a design of a single-phase shunt reactor. The half to the right is a picture of the magnetic field. The winding encloses the mid-limb with the non-magnetic gaps. A frame of core steel encloses the winding and provides the return path for the magnetic field.

3-phase reactors can also be made. These may have 3- or 5-limbed cores. See Figure 2-29. In a 3-limbed core there is strong magnetic coupling between the three phases, while in a 5-limbed core the phases are magnetically independent due to the enclosing magnetic frame formed by the two yokes and the two unwound side-limbs.

The neutral of shunt reactors may be directly earthed, earthed through an earthing-reactor or unearthed.

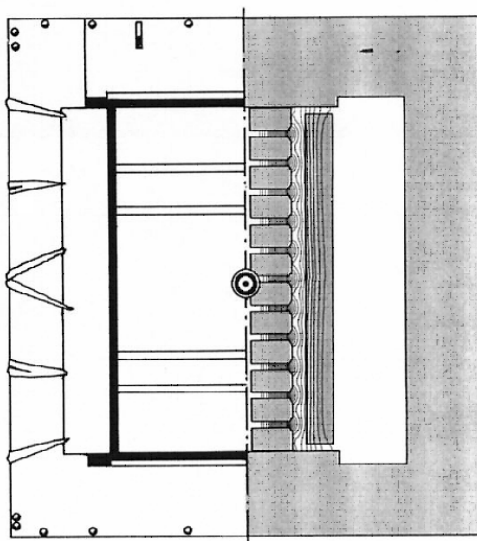


Figure 2-28

When the reactor neutral is directly earthed, the winding are normally designed with graded insulation in the earthed end. The main terminal is at the middle of the limb height, and the winding consists of two parallel-connected halves, one below and one above the main terminal. The insulation distance to the yokes can then be made relatively small. Sometimes a small extra winding for local electricity supply is inserted between the main winding and yoke.

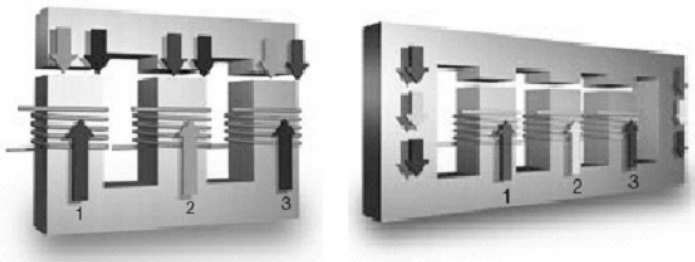


Figure 2-29

When energised the gaps are exposed to large pulsating compressive forces with a frequency of twice the frequency of the system voltage. The peak value of these forces may easily amount to 106 N/m² (100 ton/m²). For this reason the design of the core must be very solid, and the modulus of elasticity of the non-magnetic (and non-metallic) material used in the gaps must be high (small compression) in order to avoid large vibration amplitudes with high sound level as a consequence. The material in the gaps must also be stable to avoid escalating vibration amplitudes in the long run.

Testing of reactors requires capacitive power in the test field equal to the nominal power of the reactor while a transformer can be tested with a reactive power equal to 10 – 20% of the transformer power rating by feeding the transformer with nominal current in short-circuit condition.

Dielectric testing with ac voltage performed at increased frequency requires still more capacitive power in the test field. A large shunt reactor with rating 100 – 200 MVA requires at least the same amount of capacitive power as power transformer of 500 – 1000 MVA.

Since the power factor of shunt reactors is very low, loss measurements using conventional wattmeter methods may be subject to considerable errors. A bridge method may be used to advantage.

The loss in the various parts of the reactor (I²R, iron loss and additional loss) cannot be separated by measurement. It is thus preferable, in order to avoid corrections to reference temperature, to perform the loss measurement when the average temperature of the windings is practically equal to the reference temperature.

When specifying shunt reactors for enquiry, the following data should be given:

- Reactive power, Q
- Rated voltage, U
- Maximum continuous operating voltage
- Insulation level LI, SI
- Frequency, Hz
- AC test voltages
- Permissible temperature rise for oil and winding
- Sound level and linearity criteria, if required
- Type of cooling, fan, pump, radiators
- Peripheral features, if required
- Safety and monitoring equipment
- Loss capitalisation

Shunt reactors with on-load tap changers (OLTC)

Reactors equipped with an OLTC are intended to allow adjustment of the reactive compensation depending on the load condition of the line/network. During light loading the maximum reactive compensation at the tap with minimum number of turns is used and for full load conditions the reactor is switched to the tap with the maximum number of turns. A typical tapping range allows a reduction of the reactive power from 100 % to approx. 50 %.

Switching of shunt-reactors

Switching of shunt-reactors requires special precautions. In the early history of shunt reactors damage now and then occurred to the reactors during switching operations. In some cases the circuit breaker was also damaged at the same time. The reason for the failures are now well physically explained and understood, and adequate precautions to avoid, or at least reduce the probability of such failures, are available.

It is particularly when disconnecting the reactor from the power system that severe overvoltages may arise. When the breaker contacts separate, an arc starts burning between the contacts. While the arc is burning, there is still an electrical connection between the power system and the reactor. After a certain time the circuit breaker will extinguish the arc. Then the connection between the power system and the reactor is broken, and the load side of the circuit breaker with the reactor is left on its own. In many cases the arc will be extinguished before the current reaches its natural passage through zero. This means that when the arc extinguishes, a certain quantity of magnetic energy is stored in the reactor core, and the reactor has no possibility to feed this energy back to the power system. Some of the energy will remain in the reactor core as remanent magnetism, but a part of the energy will charge the stray capacitance to earth of the equipment on the load side of the circuit breaker. Since this capacitance is usually quite small, the voltage across this capacitance will be relatively high and consequently also the voltage at the reactor terminal. With some simplification we can write:

$$\frac{1}{2}L \cdot i^2 \Rightarrow \frac{1}{2}C \cdot u^2 \quad (2.5.1.1)$$

In this expression

L is the inductance of the reactor

i is the current at the moment of chopping

C is the stray capacitance of the equipment (including the reactor) at the load side of the circuit breaker

u is the voltage rise across the C

Expressed in words, (2.5.1.1) reflects that the magnetic energy in the reactor (left side of the arrow) is transformed to electrostatic energy in C (right side of the arrow). It follows that:

$$u = i \cdot \sqrt{\frac{L}{C}} \quad (2.5.1.2)$$

When using modern SF6 circuit breakers, the size of the voltage due to the current chopping is typically in the range 1,2 to 2,0 p.u. and somewhat higher for other types of circuit breakers. The rate of voltage rise is relatively moderate.

However, when the arc in the circuit breaker is extinguished, a kind of competition starts in the circuit breaker. The one competitor is the voltage increase between the two contacts in the circuit breaker, the other is the increase in breakdown voltage between the circuit breaker contacts, because the contact separation still continues and the distance between the contacts increases.

If the latter competitor wins, the voltage across the reactor will oscillate due to the energy that is flowing forth and back between the stray capacitance C and the inductance L of the reactor. The oscillation will be damped due to the resistance that always is present in a circuit. A typical course of the voltage across the reactor is shown in Figure 2-30.

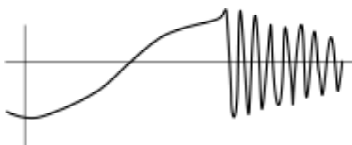


Figure 2-30

This voltage course, when disconnecting the reactor, will be harmless to the reactor and the surroundings.

The other alternative is that the voltage between the separated breaker contacts (the so-called recovery voltage) wins, which means that it at a certain moment exceeds the voltage break down voltage between the contacts. Then a new arc will arise between the contacts. This is called reignition. At reignition the voltage on the breaker contact on the load side very quickly changes to nearly the same voltage as the breaker contact on the source side. This voltage change may take place in the course of a small fraction of a microsecond. The voltage on the reactor terminal will closely follow the voltage on the breaker contact.

The extremely rapid voltage change is followed by a damped oscillation of very high frequency. Even new arcs followed by reignitions may occur before the disconnection of the reactor is finalised. in Figure 2-31 shows a typical voltage course on the reactor terminal with just one reignition in the circuit breaker.

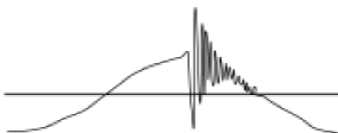


Figure 2-31

During such a voltage course the reactor winding is highly stressed, especially at the beginning of the winding. These stresses may exceed the stresses that the winding is exposed to during the standard transient voltage tests and may lead to breakdown in the winding. The stresses in the winding are not only dependent on the size of the voltage change but also on how fast the voltage changes (du/dt). So even transient voltages with peak value below the surge arrester protection level may damage the reactor.

The root of the problem is the reignitions that may occur in all types of circuit breakers (SF6, vacuum, oil, compressed air). A way to eliminate reignitions in the circuit breaker and thereby avoid damage to the reactor and equipment in the surroundings is to apply synchronous opening of the circuit breaker, also called point-on-wave controlled opening. The principle is illustrated in Figure 2-32.

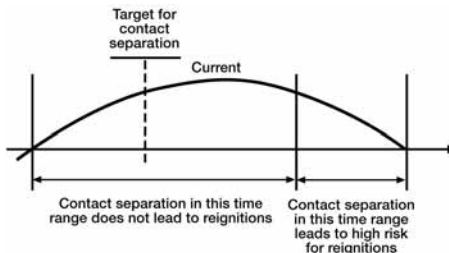


Figure 2-32

By starting the contact separation at a certain level on the rising part of the current curve, the level being sufficiently high to avoid that the circuit breaker does not chop the current, the arc will burn until the current has passed its maximum value and proceeds further towards its natural passage through zero. At a certain level before the current reaches zero the circuit breaker will extinguish the arc and chop the current, but then the contacts have had sufficient time to separate quite far from each other. Consequently the break down voltage of the distance between the contacts has also increased to a value high enough to prevent the recovery voltage to cause a break down (reignition).

The signal for synchronisation comes from a capacitor voltage transformer (CVT).

Since synchronised switching was introduced, shunt reactor failures attributable to switching operations seem to have disappeared. Encouraged by this good service experience ABB always recommends equipment (SwitchsyncTM, [4]) for synchronised switching when offering circuit breakers for shunt reactor switching.

More detailed information on controlled switching can be found in [4], available on request to the nearest ABB office.

2.5.2. Current limiting reactors

Current-limiting reactors are series reactors intended to reduce the short circuit currents in the power system. The motive to reduce the short circuit currents is to use circuit breakers with lower short circuit current breaking capacity and consequently less expensive circuit breakers.

Sometimes other system components also need protection against too high short circuit currents, like for instance auto-connected transformers that are not self-protecting due to their low impedance.

Another application is limitation of the inrush current when starting large motors.

Current-limiting reactors are sometimes used to limit discharge currents of capacitor banks. In such cases a bifilar wound resistance wire is included and connected in parallel with the inductance.



One phase of a dry-type reactor with a lifting device assembled

Dry-type current-limiting reactors

For moderate voltages and power ratings the cheapest type of current limiting reactors is usually the simple, naked dry-type reactor without iron core and any enclosure, cooled by natural air circulation. Numerous reactors of this type are in operation around in the world, most of them probably in medium high voltage power systems.

The magnitude of the inductance of these reactors is normally in the order of millihenry. The inductance remains constant when short circuit current flows through the reactor. There is no decline in the inductance due to saturation in an iron core.

The conductor material in the winding may be either copper or aluminium. The insulation and the supporting materials for the winding are nowadays synthetic, frequently with a high temperature class. When short circuit current due to failure in the power system flows through the reactor high mechanical forces arise in the reactor, within each phase winding as well as between phases. The reactors must be designed to withstand these forces, which often determines the dimensioning of the reactor.

The absence of an iron core makes the winding capacitance to earth quite small, which gives the advantage that the voltage distribution within the winding deviates just moderately from linearity during transient voltage conditions.

Figure 2-33 shows a sketch of one phase of such a reactor. The two rectangles illustrate the outer contours of the winding. a is the total height and r is the radial width of the winding. D is the mean winding diameter. The inductance is proportional to the square of the number of turns, D and a factor that depends on the quotients a/D and r/D .

The mutual inductance between the phases comes in addition, depending on the distance between the phases and whether the phases are placed above each other or besides each other, see Figure 2-34.

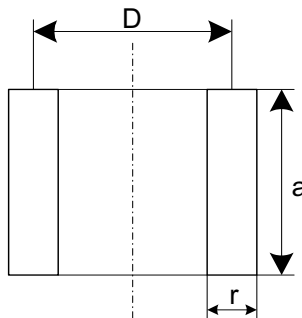


Figure 2-33

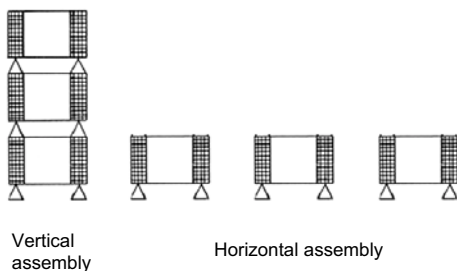


Figure 2-34

The air core reactors may require relatively large space because the magnetic field spreads freely in the surroundings and may cause excessive heating in iron reinforcements in concrete walls, floors and ceilings, wire fences and other metal items. Appropriate distance from the reactors must then be kept.

The distance should be sufficiently large to keep the magnetic field below 80 A/m at the floor and at the ceiling. At adjacent wall the magnetic field should not exceed 30 A/m.

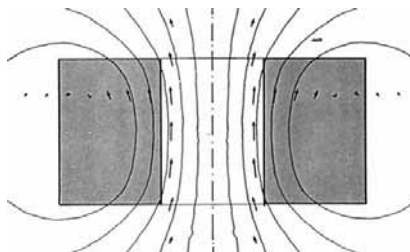


Figure 2-35

These field values are referred to continuous rated current through the reactor or to temporary currents lasting more than a few minutes.

The thermal time constant of reinforcement iron and wire fences is short. The supplier should inform the purchaser regarding necessary distances from the reactor, at which the magnetic field values have declined to those mentioned above.

Figure 2-35 illustrates the magnetic field attributed to an air-core reactor without any shield. Considerable forces due to the field can draw loose iron items in the vicinity into the reactor and cause damage. So it is recommended to keep the surroundings clean.

Possible disturbing influence of the magnetic field on the functioning of other electrotechnical product in the vicinity must be considered.

Humans should not regularly stay for longer time near the strong magnetic field from such reactors when current is flowing through the windings.

NOTE: Persons bearing pacemaker should stay far away from such reactors.

Oil-immersed current-limiting reactors

Dry-type reactors for higher voltages may not be suitable in heavily polluted areas because of the risk of dielectric failure. In such cases oil-immersed reactors might be more reliable.

To avoid excessive heating in the tank a frame of laminated core steel must enclose the oil-immersed reactor winding. See Figure 2-36. A core steel limb with gaps in the centre of the winding may not be necessary. The dimensioning of the reactor must be such that the inductance is sufficiently large when short circuit current flows through the reactor and when saturation may occur in the core.

The eddy current losses in the windings of reactors without a gapped centre limb of laminated core steel are quite high because of the strong magnetic field where the winding conductors are situated. A gapped centre limb would reduce these eddy losses, but on the other hand the core would be more complicated and costly.

The magnetic field can also be shielded by means of plates of highly conductive materials like copper or aluminium. However, the losses will be high in the shields due to the high counter-circulating currents, so this shielding method is only applicable for smaller reactor power ratings.

The cost of an oil-immersed reactor will be considerably higher than of a dry-type, while the oil-immersed reactor might be less space consuming.

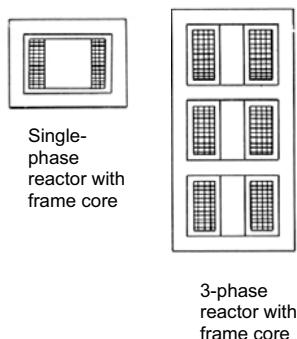


Figure 2-36

When enquiring for a current-limiting reactor, the following information should be given:

- System voltage;
- Frequency;
- Short circuit power of the feeding system;
- Insulation level;
- Rated continuous current and/or rated short-time current and duration;
- Rated impedance of the reactor or alternatively, the reduced short circuit power after including the impedance contribution from the reactor;
- Dry-type or oil-immersed;
- Indoor or outdoor installation.

2.5.3. Neutral earthing reactors

The neutral point of power systems can either be directly earthed or, at the other end of the scale, isolated. Both alternatives have their advantages and drawbacks.

Direct earthing gives the lowest voltage on the healthy phases during a single-phase earth fault. It offers also economic saving through the possibility to apply lower insulation level in the neutral end of the transformer winding. The drawback is the high failure current, which the equipment has to cope with.

Isolated neutral or earthing through high inductive impedance limits the failure current, but the voltage on the healthy phases during a single-phase earth fault will be higher. (See Figure 15-1 page 165, the part of the diagram for positive (inductive) values of X_0/X_1).

Earthing through an arc-suppression reactor (also called resonant earthing), is a high impedance earthing, which gives low failure current. (See section 2.5.7). The voltage on the healthy phases during single-phase earth fault will, however, be nearly the same as when the neutral is isolated.

Neutral-reactor earthing is an earthing with relatively low-impedance, somewhere between direct earthing an isolated neutral, limiting the failure current to an acceptable level without involving too high voltage on the healthy phases.

Under normal system conditions the voltage across a neutral-earthing reactor is small and consequently, the current through the reactor is also small. During system fault the current will increase considerably, and its duration is usually limited to 10 seconds.

Losses in neutral-earthing reactors are without economic importance. The designed current density in the winding is determined by the reactor's ability to withstand the mechanical forces due to the short-time fault current.

The design can be dry-type with air core or oil-immersed with a gapped core or with a magnetic shield. In the latter cases the inductance of the reactor must be high enough under system fault conditions to limit the failure current to the intended value.

The insulation level at the terminal connected to the system neutral is usually the same as the insulation level of the neutral. In a lightning impulse test on the reactor a test impulse with a longer front time than 1,2 μs , up to 13 μs , may be applied. The reason is that the front time of a lightning surge from the line will be prolonged when it passes through the transformer winding before it hits the reactor.

The insulation level at the earthed terminal of the reactor may be made lower than at the other terminal.

2.5.4. Capacitor damping reactors

Capacitor damping reactors are used for limiting the inrush currents occurring during the switching of capacitor batteries to a.c. networks. They are connected in series with the capacitors.

During normal operation the capacitor rated current flows through the damping reactor. The maximum permissible (overload) current of the damping reactor is equal to the corresponding value of the capacitor battery as called for in relevant standards for power (shunt) capacitors.

Reactors are also used to detune capacitor banks to avoid resonance with the power system.

Capacitor damping reactors are single-phase or three-phase, usually dry-type, self cooled, with air core, for indoors or outdoors installation.

Capacitor damping reactors are able to withstand a rated inrush current which must be high enough to cover all recognised cases of switching the capacitor battery or battery sections. The system planner must provide information to the reactor supplier regarding the relevant inrush resonant frequency. The reactor supplier supplies information about the Q-factor (the ratio reactance to resistance) of the damping reactor at this frequency.

2.5.5. Tuning (Filter) reactors

Tuning reactors are connected with capacitors to tuned filter circuits with resonance in the audio frequency range to reduce, block or filter harmonics or communication frequencies. The tuning reactors are connected either in a parallel configuration in the system (with system voltage applied across them) or in a series configuration (with load current flowing through them).

Figure 2-37 illustrates the two main types of filters in their basic forms.

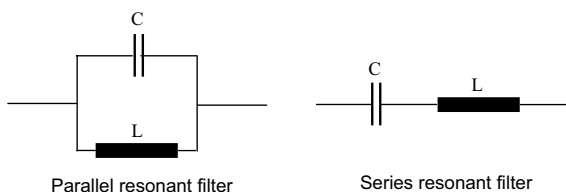


Figure 2-37

A parallel resonant filter has a high impedance that blocks for currents of a certain frequency, while a series resonant filter has a low impedance that leads away currents of a certain frequency from parts of the power system where are undesired.

Filters are preferably located as close as possible to the spot where the harmonics are generated.

Tuning reactors are single-phase or three-phase reactors, oil-immersed or dry-type. The reactors may be designed with means for adjusting the inductance value within a limited range either by tapplings or by movement of core and/or coils. The preferred or recommendable design solution in each particular case should be indicated already in the enquiry or the tender.

Naked dry-type air core reactors might offer the lowest purchase price. However, when erected outdoors at moist and heavily polluted locations, such reactors may be more vulnerable to dielectric failure than oil-immersed reactors.

Tuning reactors for audio frequency signals may be equipped with a second winding connected to the audio frequency source or to other components.

When connected in parallel configuration the reactors are subjected to inrush transients at switching operations. When connected in series configuration they are also subjected to overcurrents due to system faults, which they must withstand under recognised conditions.

In three-phase filter circuits attention should be paid to the magnetic coupling between different reactor phases.

A current with the frequency of the power system flows through the reactor winding. In addition comes a current of the resonance frequency of the filter circuit where the reactor is a component. The latter current may be continuous or intermittent. The sum of these two current components is one of the parameters that determine the dimensioning of the reactor.

The voltage across the reactor is the sum of the voltage drop due to the power frequency current and the tuning frequency current.

The rated inductance L of the reactor is referred to the tuning frequency.

When designing a tuning (or filter) reactor the value of the maximum short-time current and its duration must be known.

The spectrum of signal frequency voltage and current in the system should also be known.

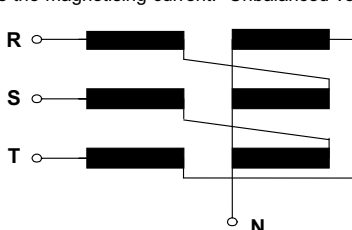
A property of interest is the Q -factor of the reactor, which is the ratio between the reactor reactance and resistance at tuning frequency and reference temperature.

The insulation level of tuning reactors corresponds usually to the highest voltage for equipment U_m of the system where the reactor is installed, unless particular reasons motivate a different level. If one terminal of the reactor is intended for direct earthing, non-uniform insulation may be applied. If an audio signal reactor has a second winding, this winding should be designed with consideration of possible transferred overvoltages from the power system.

2.5.6. Earthing transformers (Neutral couplers)

Earthing transformers are used to create a neutral point in a three-phase system, which provides possibility for neutral earthing. The earthing can be through an arc-suppression reactor (see 2.5.7 page 47), a neutral earthing reactor (see 2.5.3 page 44) or resistor or directly.

The design can be a transformer with just one winding, which is zigzag connected. The zero sequence impedance of such a winding is normally quite low, but it can be increased if the purpose is to limit the current through the transformer in case of an earth fault somewhere in the system. Figure 2-38 shows the connection diagram. During undisturbed system operation with balanced (symmetrical) voltages the current through the earthing transformer is small and of the same size as the magnetising current. Unbalanced voltages will cause some higher currents flowing through



the earthing transformer, which it must be capable to carry.

An alternative connection to the zigzag is star/delta connection where the delta connected winding will compensate the zero sequence magnetic field so it will be confined to a leakage field between the star and the delta winding and make the zero sequence impedance of the transformer relatively small. However, if it is desired to increase the zero sequence impedance, this can be achieved by opening the delta connection and insert a reactor or resistor.

Figure 2-38

It is possible to provide the earthing transformer with a secondary winding for continuous auxiliary station supply.

Earthing transformers are usually oil immersed and may be installed outdoor. In cases where a separate reactor is connected between the transformer neutral and earth, the reactor and the transformer can be incorporated in the same tank.

When the earthing transformer is going to be used together with an arc-suppression reactor, the rated current (and its duration) of the earthing transformer will be determined by the data for the arc-suppression reactor.

If the earthing transformer is used for directly earthing or through a current limiting reactor, the neutral current through the transformer will be high but the duration is limited to a few seconds. Earthing transformer must be designed to withstand the thermal and mechanical effects of the rated neutral current.

The characteristic of earthing transformer should be selected to match the property of the system. See section 15.1.1 page 165.

Most of the time in service the loading of earthing transformers is very low. It is the randomly occurring short-duration currents that cause any heating of significance. Ageing of the cellulose materials is then not a matter of concern. Regarding acceptable temperatures there are two aspects to consider:

The temperature during currents of say 10 seconds duration must not cause softening of the winding conductor material, say 250 °C for copper and 200 °C for aluminium. (See Table 3 in IEC 60076-5 (2000-07) Power transformers – Part 5: Ability to withstand short circuit).

For currents with duration in the order of hours or more, temperatures that cause excessive gas development in the oil should be avoided. Temperatures for items in direct contact with the oil should then not exceed 140 °C.

The system earth fault protection relay may not be effective at low currents. To prevent damage to earthing transformer by such current, oil thermometer with alarm/trip contacts is recommended. Alternatively the value of maximum continuous earth fault current may be declared and sensitive protection provided.

For earthing transformers that carry continuous load because of a secondary winding that supplies local consumers, the temperature limits in IEC 60076-2 (1993-04) Power transformers Part 2: Temperature rise apply.

2.5.7. Arc suppression reactors

Arc-suppression reactors are also named earth fault neutralisers or Petersen-coils after W. Petersen who launched the idea of this particular reactor application early in the previous century.

Background

In high voltage power systems single-phase earth faults may take place. These may be initiated by transient overvoltages, often combined with reduced dielectric strength due to contaminated insulators or the presence of animals like birds, squirrel etc. Arcs arise which lead capacitive currents. If the current is above certain levels, the arc may last for a long time and cause conductor rupture and damage to material like insulators. It may even cause fire.

It is generally assumed that arcs extinguish by themselves when the arc current is below 5-10 A. The purpose of the arc-suppression reactor is to reduce the arc current and thus provide the condition for the arc to extinguish. In order to determine the appropriate inductance of an arc-suppression reactor it is necessary to know the earth-fault current. This is in turn given by the capacitance to earth C_e of each phase conductor of the power system.

Basic principle of the arc-suppression reactor

To illustrate the effect of an arc-suppression reactor we will use an example, which is somewhat simplified but still sufficient to explain the principle.

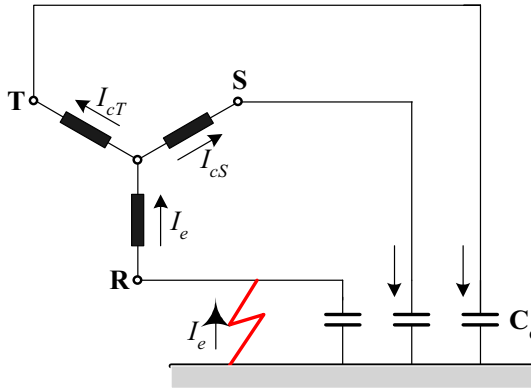


Figure 2-39

Figure 2-39 shows to the left an energy source that might be a secondary winding of a transformer with the terminals R, S and T. It is connected to a system where each phase has a capacitance to earth C_e . This capacitance is distributed along the whole length of the conductors, but is indicated as one concentrated capacitor C_e per phase. Assume that this capacitance is the same in all three phases, which means that the phase conductors of overhead lines are perfectly revolved.

An earth fault is indicated in phase R. For the sake of simplicity we assume that the impedance at the failure spot is so small that it can be neglected. In other words, the potential of phase R is equal to the earth potential, which in undisturbed and symmetrical condition lies in or close to the neutral point (star point) of the transformer winding.

Due to the earth fault the potentials to earth of phases S and T have increased. In normal operation there is an exchange of currents between the system and earth in such a way that the capacitance to earth of one phase serves as return path for the current through the capacitance of the two other phases and vice versa.

The earth fault has altered this capacitive current flow. Now the return of the current to earth from phase S and T goes through the earth fault and into phase R. Because of the increased potentials to earth of phase S and T, the currents to earth from these phases have also increased. The vector relationships between voltages and currents are shown in Figure 2-40.

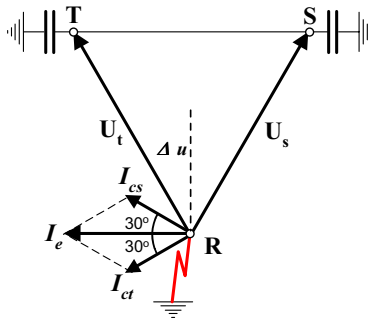


Figure 2-40

In this example the potential in relation to earth on the sound phases S and T is assumed to be equal to the normal system voltage U (line-to-line). In other words, the potential to earth on these phases has increased by a factor of $\sqrt{3}$. (This factor may in practice be lower or higher than $\sqrt{3}$). The neutral has shifted Δu , which in this case is equal to the normal line-to-neutral voltage.

The capacitive currents to earth from phase S and T, I_{cs} and I_{ct} are leading 90° in relation to U_s and U_t respectively. The capacitive current in the earth fault, I_e is the vectorial sum of I_{cs} and I_{ct} .

$$I_{cs} = I_{ct} = U \cdot \omega \cdot C_e \quad (2.5.7.1)$$

$$I_e = 2 \cdot U \cdot \omega \cdot C_e \cdot \cos 30^\circ = \sqrt{3} \cdot U \cdot \omega \cdot C_e \quad (2.5.7.2)$$

Depending on C_e , which is proportional to total length of lines and cables in the system, I_e may become quite high and may sustain an arc at the failure spot.

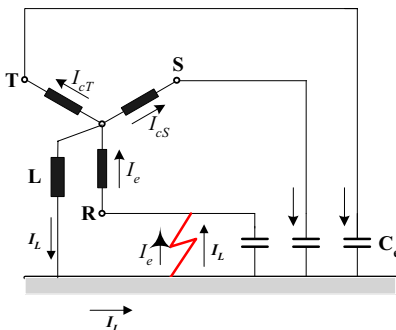


Figure 2-41

When connecting an arc-suppression reactor L between the neutral of the transformer winding and earth, an inductive current flows through L to earth where it finds its return path through the earth fault. The inductive current through the earth fault has the opposite direction of the capacitive current provided by phases S and T.

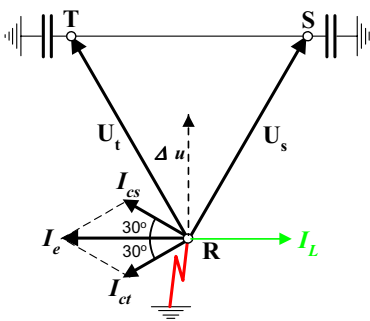


Figure 2-42

Figure 2-42 shows the I_L vector added to the previous vector diagram in Figure 2-41 before the presence of the arc-suppression reactor. Δu is the voltage that drives the current I_L through the reactor, and I_L is naturally lagging 90° in relation to Δu .

By adjusting the reactance of the reactor I_L can be given the same numerical value as I_e , and because I_e and I_L have opposite directions, the resulting current through the fault will become zero or close to zero. Then the arc at the failure spot is given a high probability to extinguish by itself, and the operation of the power system can continue undisturbed and without any interruption of the electricity supply.

Determination of reactor data

As described in the previous section the current through the reactor shall equalise the capacitive current determined by the capacitance to earth of the system where the reactor is to be installed. Then it is necessary to know C_e .

C_e can be found by direct measurement in the power system. However, the system might rarely be at disposal for such measurements, so C_e must then be estimated on the basis of calculations.

Systems may contain both overhead lines and cables, and one kilometre of cable has a much higher capacitance to earth than one kilometre of overhead line. The contribution to C_e from the cables can be calculated based on specific data from the cable suppliers and the total length of the cables.

The contribution to C_e from the overhead lines might not be just as easily to determine with the same accuracy as for cables. C_e for overhead lines is determined by several parameters such as:

- the height of the conductors above the earth;
- the geometric configuration of the three phase conductors
- the number of parallel conductors per phase;
- the number of earth wires, if any, and their distance to the phase conductors and to the earth;
- the dimensions of the conductors;
- the extent of vegetation below the line;
- seasonal variations due to ice and snow.

Exact formulas for the capacitance to earth under idealised conditions (plane earth, constant distances to earth and between conductors) are deduced in the literature, for example [2]. However, taking into consideration that the reactance of arc-suppression reactors can be varied within wide limits, simpler approximate calculation methods of C_e will be sufficient for the purpose.

Hunter and Light [3] have found some typical values of C_e of overhead lines at a number of different service voltage levels, and corresponding earth fault currents per kV system voltage and km line length have then been calculated by means of equation 2.5.7.2. The result is shown in Table 2-1 below.

Table 2-1

System voltage	Earth fault current
kV	A/(kV*km)
13,8	0,00453
23	0,00339
34,5	0,00302
46	0,00297
69	0,00286
92	0,00302
115	0,00313
138	0,00318
161	0,00333
230	0,00365

Figure 2-43 a and b shows typical charging currents (earth fault currents) in an overhead line system as functions of the line length, with the system voltages as parameters. The diagrams are valid for 50 Hz. For 60 Hz the currents must be increased by 20%. From these diagrams the capacitive fault current can easily be estimated. The nominal current of an arc-suppression reactor should be the same as the capacitive fault current, which means that the reactor must be capable to carry this current for a certain time, and in addition, the reactance of the reactor must be such that it lets this current through when a certain voltage appear across the reactor. This voltage shall be the highest voltage the reactor will be exposed to in service. In practice this is taken as the highest system voltage divided by $\sqrt{3}$. That is the phase-to neutral voltage when the system is balanced (symmetrical).

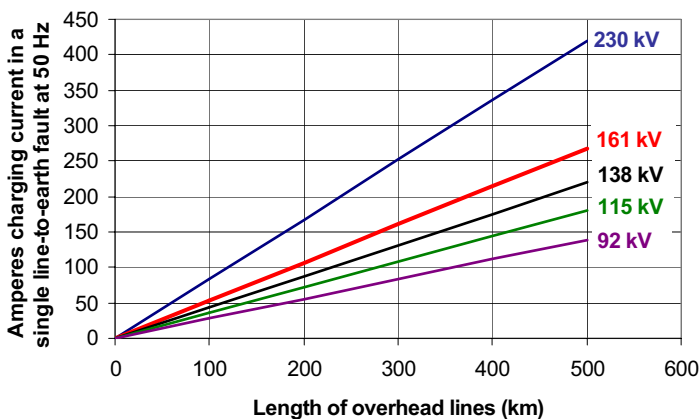
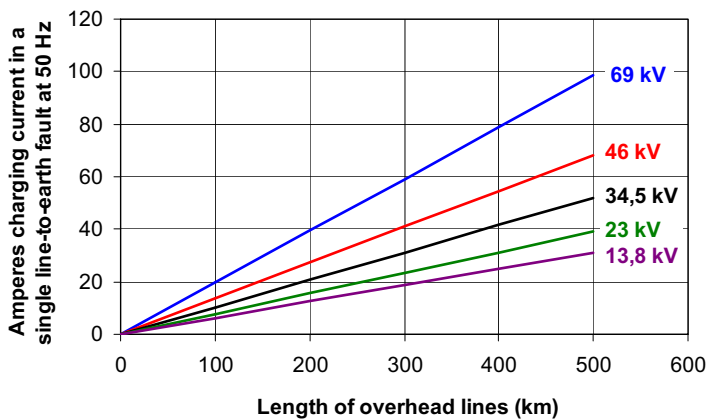


Figure 2-43

When also cables are parts of the system, the contribution from the cables to the earth fault current must be taken into account. This should preferably be based on information from the cable suppliers, but in case such information is lacking, we provide some data as guidance.

The capacitance to earth of cables may vary within a range of 0,1 – 0,7 $\mu\text{F}/\text{km}$ depending on the cable design and dimensions. We consider three different designs, which are shown in Figure 2-44.

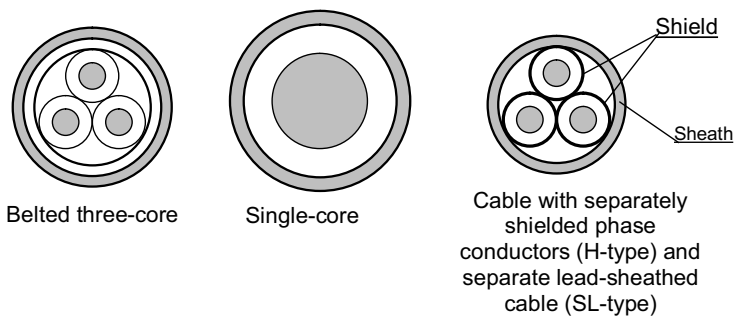
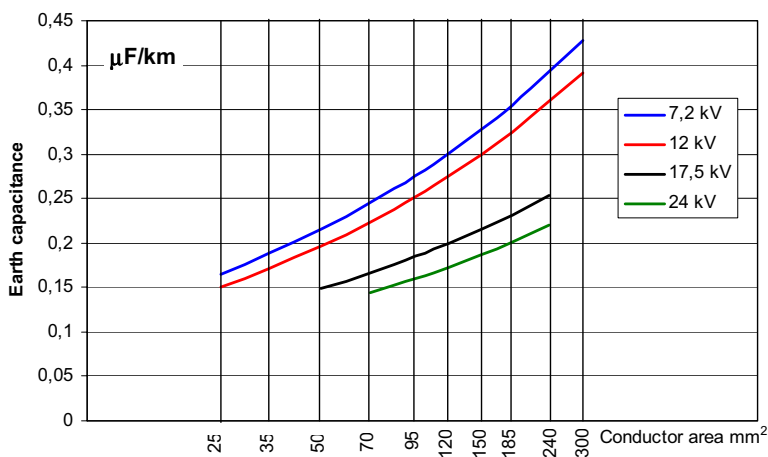


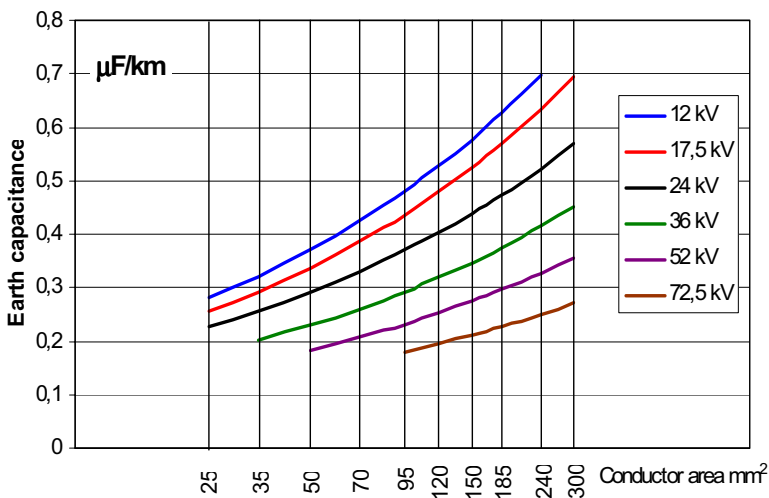
Figure 2-44

The earthing capacitance for each phase, C_e , expressed in $\mu\text{F/km}$ cable is indicated on the ordinate axis in the following Figure 2-45, Figure 2-46 and Figure 2-47.



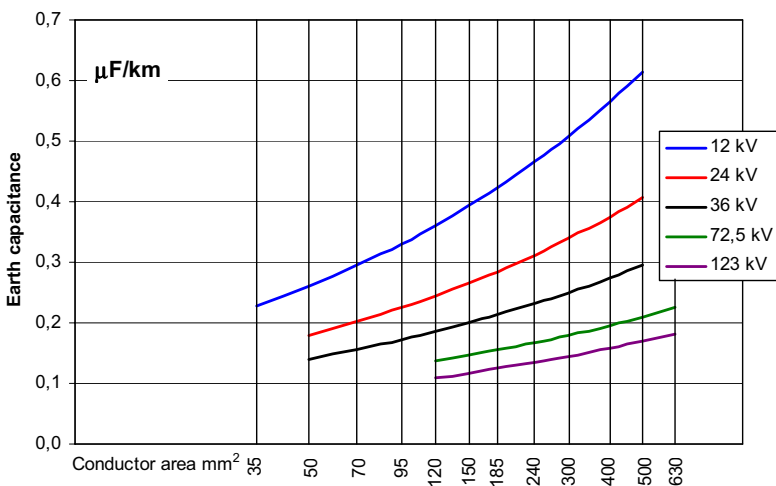
Conductor –to-earth capacitance C_e of belted three-core cables as a function of conductor cross-section. Paper insulation

Figure 2-45



Conductor-to-earth capacitance C_e of single-core, SL- and H-type cables as a function of conductor cross-section. Paper insulation.

Figure 2-46



Conductor-to-earth capacitance C_e of XLPE-insulated cables as a function of conductor cross-section.

Figure 2-47

To determine the capacitive earth fault current based on the diagrams in Figures 2-45, 2-46 or 2-47 the ordinate Y read from the conductor area on the x-axis and the curve for the relevant system voltage should be inserted in the following formula:

$$I_e = \sqrt{3} \cdot 2 \cdot \pi \cdot f \cdot Y \cdot U \cdot L_c \cdot 10^3 \quad (2.5.7.3)$$

In this formula

I_e is the capacitive earth fault current in amperes;

f is the power frequency;

Y is the ordinate from one of the diagrams in Figure 2-45, Figure 2-46 or Figure 2-47 in $\mu\text{F/km}$;

U is the system voltage (line-to-line) in kV;

L_c is the total length of the actual type of cable in the system in km.

The total capacitive earth fault current

The total capacitive earth fault current is determined by adding arithmetically the contributions from the overhead lines and from the cables. The rated current of the arc-suppression reactor should be at least the same as the total capacitive earth fault current. Preferably future extensions should also be taken into account. In general the rated current of the reactor should not be too small. In case of imperfect tuning of the reactor the residual reactive current should be inductive. A capacitive residual current may cause that the voltage to earth on the healthy phases becomes still higher than the line-to-line system voltage.

Design

Arc-suppression reactors are single phase. They have a core consisting of steel sheets, just like transformer cores. In most cases the core has a centre limb, which is enclosed by the winding, and two unwound side limbs and the upper and lower yokes close the magnetic path. The core differs from transformer cores, since the centre limb consists of a number of core steel packets with non-magnetic gaps in between.

The winding is similar to transformer windings. It may have tapplings for tuning the reactance to the capacitance to earth of the system. The reactance can be varied within a certain range. The relation between the highest and the lowest reactance is for practical reasons limited to 2,5:1. For lower system voltages (22 kV and lower) the relation can be 3:1.

If larger a range is required, 10-12:1 can be achieved by regulating the gaps in the core. Regulation of the gaps can be made by means of an electric motor. This regulation is continuous, while regulation by means of tapplings in the winding is in steps.

In established systems where the situation is quite stable, that is, there are no or very rare changes in the earth capacitance of the system, reactance adjustment in steps by means of an off-circuit tap-changer will be adequate. In systems, which are subject to frequent extensions or sectionalising, automatic tuning by varying the gaps in the core may be preferred.

Arc-suppression reactors are oil-immersed in most cases.

Arc-suppression reactors are normally equipped with a secondary winding for indication and measurement of the voltage across the reactor. The secondary winding is sometimes loaded with a resistance in order to increase the active component of the failure current to activate selective earth-fault relays in case of a permanent earth fault. An arc-suppression reactor does of course not remove an earth-fault when for example a conductor of an overhead line has fallen down to the earth. However, the reactor can in such cases limit the material damages by minimising the fault current.

Normally arc-suppression reactors have a built-in current transformer for indication and measurement of the current through the reactor.

System connection

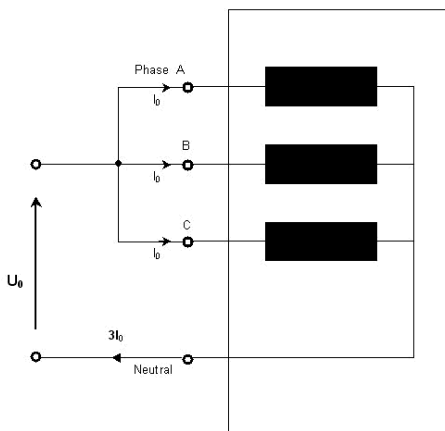
Arc-suppression reactors are connected between the power system neutral and earth. The system neutral may be available at the neutral bushing of star- or zigzag-connected transformer windings. If a transformer with such a winding is missing at the location where installation of an arc-suppression reactor is desired, an earthing reactor (also called neutral coupler) can provide a neutral point. (See 2.5.3 page 44).

When determining the reactance of an arc-suppression reactor, the zero sequence reactance of the transformer or earthing reactor must be taken into account. This zero sequence reactance comes in series with the reactor reactance. It is then the sum of reactor reactance and one third of the zero sequence reactance of the connected transformer or earthing reactor that shall equalise the system capacitance. To determine the reactance of the arc-suppression reactor, the zero sequence reactance of the transformer where it is connected must be known.

Transformer zero sequence impedance

IEC 60076-1 (1993-03) Power transformers Part 1: General, defines the zero sequence impedance of a three-phase winding as the impedance, expressed in ohms per phase at rated frequency, between the line terminals of a three-phase star-connected or zigzag-connected winding, connected together, and its neutral terminal.

This can be found by measurement in the following way:



Measurement of zero sequence impedance

Figure 2-48

The zero sequence impedance in ohm/phase is given by

$$Z_0 = \frac{U_0}{I_0} \quad (2.5.7.4)$$

The zero sequence impedance may also be expressed in per cent of the reference (or base) impedance of the transformer Z_{ref} :

$$z_0 = \frac{Z_0 \cdot 100}{Z_{ref}} \quad (2.5.7.5)$$

$$Z_{ref} = \frac{U^2}{S_r} \quad (2.5.7.6)$$

in which U is the rated voltage (line-to-line) in kV and S_r is the reference power rating of the transformer in MVA.

The zero sequence impedance may have several values because it may depend on how the other winding or windings are connected or loaded. The key question is whether any other winding provide balancing ampere-turns or not.

If there is a delta-connected winding in the transformer, balancing ampere-turns will be provided by a current circulating within the triangle of the delta-connected winding. In this case the zero sequence impedance will be approximately equal to the plus and minus sequence short-circuit impedance of the pair of windings, star and delta.

Zigzag-connected windings have the special property that they can be connected in such a way that they provide balancing ampere-turn themselves, because currents equal in size with opposite polarity flow through the two halves of such windings on each of the three limbs. The current creates a magnetic leakage field between the two winding halves, and the zero sequence reactance of the zigzag-winding becomes low and equal to the short circuit reactance between the two halves.

Yyn-connected transformers (without any tertiary delta-connected winding) have very high zero sequence reactance, 30-100% or even more. If the core has 5 limbs or if it is a shell-type transformer or if three single-phase transformers are connected star-star in bank, the zero sequence impedance will be of the same order as the magnetising impedance because there is no possibility for counteracting ampere-turns in any other winding. When connecting an arc-suppression reactor to YNy- or Yyn-connected transformers, it may be necessary to reduce the reactance of the reactor by one third of the zero sequence reactance of the transformer. If the zero sequence reactance of the transformer is neglected, the reactance of the arc-suppression reactor should be:

$$X_L = \frac{1}{3\omega C_e} \quad (2.5.7.7)$$

When the zero sequence reactance of the transformer is high compared to $1/3\omega C_e$, X_L should be adjusted according to:

$$X_L = \frac{1}{3\omega C_e} - \frac{X_{0t}}{3} \quad (2.5.7.8)$$

where X_{0t} is the zero sequence reactance of the transformer.

Another aspect of connecting arc-suppression reactors to transformers where the zero sequence magnetic field flows uncompensated, like in YNy- and Yyn-connected transformers, is that this magnetic field may cause excessive heating in the tank wall and in clamps keeping the laminated steel plates of the core together. The thermal time constant for these items is short, so the heating is noticeable in the course of few seconds. Such excessive heating may cause gas development in the oil and even gas bubbles that may jeopardise the safe operation of the transformer. If the duration of the fault current is limited to just a few seconds, such potential risk can be disregarded. Longer duration loading of the transformer neutral should be clarified with the transformer supplier.

The neutral of zigzag-connected windings is always suitable for connection of an arc-suppression reactor, regardless of any other winding on the core. The neutral of star-connected windings is also suitable for connection of an arc-suppression reactor, provided that the transformer that the star-connected winding belongs to has another winding that is delta-connected.

Operational characteristics

A question of far-reaching importance is how long the involved parts of the power system is permitted to operate with a single-phase earth fault that does not disappear after a few seconds, before the section where the failure is located must be disconnected from the voltage source. This question does not only involve the dimensioning of the arc-suppression reactor and the design of the transformer where it is connected. It involves also in general the choice of surge arresters in the system. The temporary overvoltage to earth on the healthy phases during a single-phase earth fault and its duration determines the choice of surge arresters, their protection level, the insulation level of system components and the safety margin between the insulation level and the arrester protection level.

Tuning

Setting of the reactance of an arc-suppression reactor (or tuning the reactor) can be made without making any artificial earth fault by deliberately connecting one phase of the system to earth. In many cases the capacitances to earth are not exactly equal in all three phases. This causes a certain displacement of the neutral. In other words, there will be some voltage across the arc-suppression reactor, which can be read on a voltmeter connected to the low voltage measurement winding of the reactor. When the reactance of the reactor is varied, the neutral displacement and the voltage across the reactor will also vary. The reactor is in resonance with the capacitance to earth of the power system when the neutral displacement and the voltage across the reactor have their maximum.

The capacitance to earth in cables are quite equal and if cables is a dominant part of the system in relation to overhead lines, the neutral displacement might become too small to make use of this tuning method. In such cases installing a suitable capacitor to earth in one of the phases can provide an unbalance, which gives an adequate neutral displacement.

Maximising the neutral displacement is also the basic principle for automatic tuning of the reactor in service.

After a period when circuit breakers with fast re-closure frequently were installed instead of arc-suppression reactors in order to solve the earth fault problem, the arc-suppression reactors now seem to obtain some of a renaissance. The reason is probably the continually increasing dependence of reliable electricity supply in the society. Due to the use of more and more modern electronic equipment even very short interruptions in the electricity supply causes considerable inconvenience and problems.

According to statistics earth fault arcs in adequately tuned power systems quickly extinguish in the majority of cases without any interruption in the electricity supply. Tuned arc-suppression reactors also cause a delay in re-establishing the normal service voltage to earth in the faulty phase. The risk of arc re-ignition is then reduced.

2.5.8. Smoothing reactors

The direct current that comes from the rectifier in d.c. systems has superimposed harmonic components, also called ripple. The smoothing reactor is connected in series rectifier (converter) and the whole load current, including the d.c. current and small a.c. harmonic currents, flows through it.

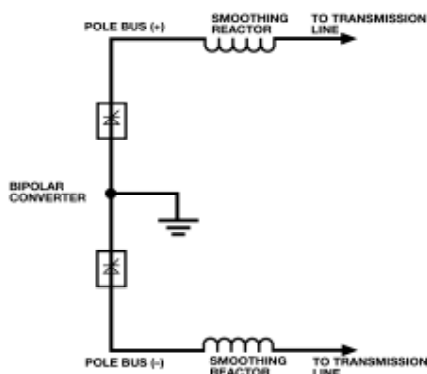


Figure 2-49



Oil-immersed smoothing reactor in the Rihand - Dehli HVDC transmission

The purpose of the reactor is to provide high impedance to the flow of the harmonic currents, reduce their magnitude and thus making the d.c. current more smooth. The higher reactor inductance the smaller remaining harmonic currents (ripple), but at the same time higher reactor costs and losses. The voltage drop across the reactor is the notches in the voltage from the rectifier.

A smoothing reactor has no nominal power rating in the same sense as a.c. reactors. However, a size comparison can be made on the base of the stored magnetic energy. In this respect the size of a smoothing reactor in HVDC systems can be much higher than even the largest shunt reactors, which also is reflected in the physical dimensions. Sometimes it is necessary to share the winding (which naturally is single-phase) on two core limbs in order to keep the outer dimensions within the transport profile.

Besides reducing the current ripple, the smoothing reactor has other functions to cover, like:

- preventing commutation failure in the inverter by limiting the rate-of-rise of current during commutation in one bridge (the transfer of current from one valve to another in the same row in the bridge) and during collapse of voltage in another bridge;
- reducing the rate-of-rise of current if failures occur on the d.c. system;
- improving the dynamic stability of the transmission system;
- reducing the risk of commutation failure during a.c. system voltage drop.

The design may be dry-type or oil-immersed, with or without gapped iron core or magnetic shield. The magnetic characteristic may be linear or non-linear.

In large HVDC systems the smoothing reactors is operating at a high d.c. potential to earth. When dry-type air-core reactors have been used, they have been placed on platforms, which have a high insulation level to earth. Dry-type air core reactors will probably in many cases, depending on the required inductance and the service voltage, be cheaper and lighter than oil-immersed reactors. However, even dry-type air core reactor weight may amount to 25 – 50 ton, so an insulating platform must be of a mechanical robust design.

Dry-type air core reactors have a linear inductance characteristic, while oil-immersed reactors may have a non-linear inductance characteristic due to saturation in ferromagnetic core or shield, depending on the chosen flux density when designing the reactor.

The direct current flowing through smoothing reactors causes a magnetising bias where the a.c. magnetisation is superimposed. The magnetic flux will then not oscillate symmetrically around zero but around a flux value determined by the d.c. magnetisation. In the part of the cycle when the d.c. flux and the a.c. flux have the same direction, the iron core may be saturated.



Air-core smoothing reactor in the Fennoskan HVDC transmission

Figure 2-50 shows an example where the vertical red line indicates the bias d.c. magnetisation caused by the d.c. current flowing through the reactor. The two dotted horizontal lines indicate the range of linked flux variation caused by the superimposed harmonic a.c. voltage. They are located symmetrically around the d.c. linked magnetic flux. The two dotted vertical lines indicate the limits for the corresponding harmonic a.c. current. The latter limits are located asymmetrically in relation to the d.c. magnetising current.

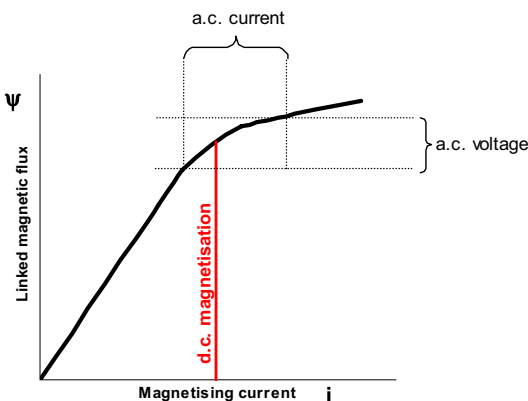


Figure 2-50

The inductance L of the reactor is defined as:

$$L = \frac{d\Psi}{di} \quad (2.5.8.1)$$

This is identical to the slope of the magnetisation curve, which varies with the magnetising current. The lower part of the curve is linear, and in this range L is constant. Where the core is completely saturated, the curve is also linear and L is also constant, but here the slope of the curve corresponds to the inductance of an air core reactor, as if the iron core does not exist. Between these two linear ranges there is a range where the curve is non-linear. In this range L is not constant but varies during the cycle of the a.c. voltage and current. The resulting L is called the incremental inductance, which is lower than the inductance in the low linear range of the curve. Consequently the reduction of the current ripple will also be lower compared to the reduction that would be achieved if the reactor were operated in the low linear range of the magnetisation curve. On the other hand, however, this would cause a more expensive reactor.

Smoothing reactors in large HVDC transmission systems manufactured by ABB are nowadays oil-immersed and designed with gapped iron core, just like large shunt reactors. For such reactors the incremental inductance is an essential parameter. It can be measured during the delivery test provided there is a sufficiently large d.c. source available in the test laboratory. Alternatively the incremental inductance can be calculated based on a recording of the magnetisation curve of the reactor.

Smoothing reactors in HVDC links are subject to special dielectric stresses when the direction of power flow in the link changes. To verify the ability of the reactor to withstand such stresses a polarity reversal test is performed before delivery from the factory. Figure 2-51 shows a voltage versus time diagram for such a test. A period with negative polarity is followed by a period of positive polarity and finally a period back to negative polarity. To demonstrate that there is a satisfactory safety margin the test voltage U_{pr} should be higher than the rated d.c. voltage in operation, for example 25% or other value, according to agreement.

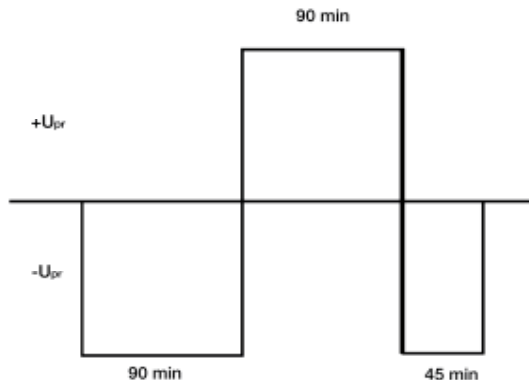


Figure 2-51

The polarity reversal test is followed by an a.c. voltage test of 1 hour duration with PD measurement.

The dielectric testing includes also a withstand test with d.c. voltage equal to 1,5 times the rated service voltage of 1 hour duration and with PD measurement.

Supplementary information is found in:

- IEC 289 (1988) Reactors, which is in the process of being revised and will be issued with the number IEC 60076-6;
- IEEE Std 1277-2000 IEEE Standard General Requirements and Test Code for Dry-Type and Oil-Immersed Smoothing Reactors for DC Power Transmission.

- Do not tamper with interlocks, alarms and control circuits,
- Be aware of possible need for magnetic field protection,
- Perform a final inspection prior to energizing:
 - All external connections have been made properly,
 - Review and check all alarm and trip functions,
 - Remove all temporary earthing connections,
 - The transformer tank is properly earthed,
 - Neutral terminals of star connected windings are correctly earthed or surge protected,
 - All connections are tight and secure,
 - All secondary circuits of current transformers are closed and earthed,
 - All accessory circuits are operational,
 - All tap connections are properly positioned,
 - The neutral and earth connections have been properly made,
 - Fans – if supplied – are operational,
 - Proper clearance is maintained from high voltage bus to terminal equipment,
 - The correct transformer ratio exists for units with internal terminal boards,
 - All windings are free from un-intended earths. A relevant megger is recommended,
 - There is continuity in all windings,
 - There is no dust, dirt or foreign material on core and coils (dry-type transformers),
 - There is no visible moisture on or inside the core and coils (dry-type transformers),
 - All plastic wrappings are removed from the core and coils (dry-type transformers),
 - All shipping members have been removed,
 - There are no obstructions in or near the openings for ventilation,
 - Cooling water supply is adequate,
 - No tools or other articles are left inside or on top of the core, coils, tank or enclosures,
 - All protective covers are closed and tightened,
- Comply with any instructions supplied by the transformer manufacturer,
- Comply with relevant Internal Control Regulations.

See also relevant safety sections on safety and protection in *Extracts from IEC 61936-1 (2002-10) Power installations exceeding 1 kV a.c. – Part 1: Common rules in Section 18 page 201 of the handbook.*

4. LOSS CAPITALISATION AND OPTIMUM TRANSFORMER DESIGN

The total transformer cost for a user consists of two main components:

1. The initial costs, that is the purchase price and the installation cost
2. The operational costs during the time in use

The initial costs generate capital costs. The operational costs consist of surveillance, maintenance, insurance, and taxes and, not the least, the costs for the energy needed to cover the losses in the transformer.

Transformer suppliers offer transformers with the user's requested power rating and voltage ratio, which in addition fulfil certain dielectric, thermal and mechanical requirements. A transformer may be designed to achieve the lowest possible purchase price. The losses of such a transformer are relatively high, and the operational costs will be accordingly high.

However, by increasing the cross section of the winding conductors and/or the core beyond the minimum needed for a reliable transformer, a wide range of transformer designs with lower losses can be achieved. The quantity of materials will be higher and naturally also the purchase price.

Figure 4-1 shows in principle how the manufacturing cost (the blue curve related to the left vertical axis) and the losses (the red curve related to the right vertical axis) vary with the transformer mass or the consumption of material. The manufacturing cost increases with increasing transformer mass, while the losses decrease with increasing transformer mass.

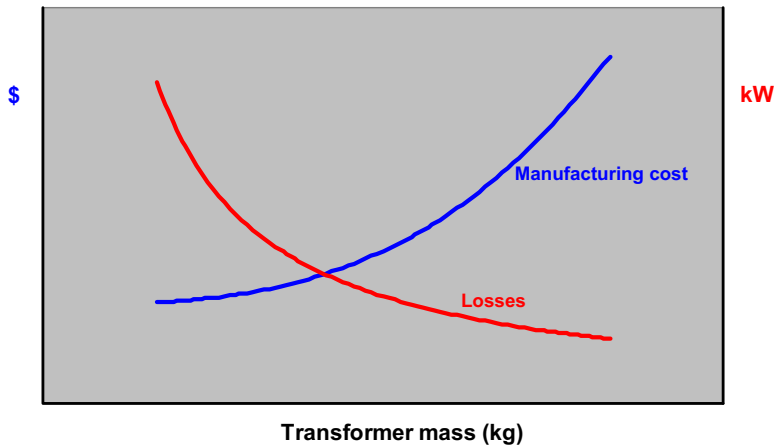


Figure 4-1

In Figure 4-2 the monetary value of the losses is inserted instead of the losses.

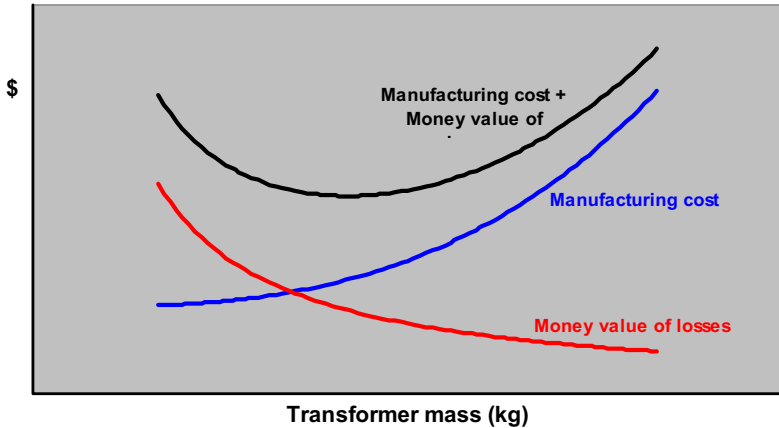


Figure 4-2

The black curve is the sum of the manufacturing cost and the money value of the losses, that is the total costs. This curve has a minimum point as can be seen in Figure 4-2.

The customer's best buy is a transformer that gives the minimum total costs, which is to be found somewhere on the scale between the minimum purchase price and the price for a transformer which from a pure technical point of view is more or less oversized. How much should then the quantity of materials be increased to obtain the optimum loss transformer?

To answer this question the designer needs already at the enquiry stage money values per kilowatt for the no load and the load losses, which must be provided by the purchaser. Based on these values the transformer designer works out the best compromise between initial cost and power loss expenditure.

The money values for the losses, the so-called capitalised loss values, express the maximum amount of money the user is willing to invest to reduce the transformer losses by one kilowatt.

We will in this chapter describe a way to achieve reasonable capitalised loss values.

The losses in the transformer are traditionally expressed in terms of two separate quantities, determined by two separate tests.

- No load loss at rated voltage
- Load loss at rated current

The no load loss figure is obtained in a test with rated voltage applied to one of the windings and all other windings open-circuited.

The load loss is by definition taken as the active power consumed in a short-circuit test where rated current of rated frequency is fed into one winding and another winding short-circuited. Possible other windings shall be open. The loss is guaranteed and determined at a reference temperature in the windings (75 °C according to International Standards (IEC), 85 °C according to ANSI/IEEE. The reference temperature for dry-type transformers depends on the type of insulation material and the corresponding permitted winding temperature).

No load loss

The no load loss is assumed to be present with its measured reference value for the whole time that the transformer is energised. No account is taken of the difference between service voltage and rated voltage, or of possible combination effects of leakage flux running through yoke parts. A system intertie transformer or receiving transformer is energised continuously, but generating sets may be started and stopped (peak load generation). Industrial process transformers may also have intermittent duty cycles.

Load loss

The evaluation of load loss is more complicated. For a transformer in general transmission or distribution duty the load has a daily variation, a weekly variation and a seasonal variation. This is then further combined with a long-term trend of generally rising loading over a number of years, until the installation becomes fully loaded and has to be relieved or reinforced. It would be practicable, with today's computer facilities, to run a summation over an estimated life cycle scenario, taking into account detailed load variations, tap-changer settings and operating temperatures with variable ambient (which is co-variant with seasonal load variation). However, in view of the considerable uncertainty of the assumptions, a much simpler method is satisfactory for the purpose. Actual temperature and voltage (tap-changer position) variations are disregarded, and only the variation of loading is used. The momentary load loss is taken to vary strictly with the square of the load.

An important aspect is that transformer installations must provide sufficient power capacity for back-up service in case of disturbance. A certain overload for a limited period of time is permissible. (However, awareness should be drawn to the fact that overloading and increased average winding temperature above 105 °C increases the probability of bubbling in the oil, which under unfortunate circumstances may cause dielectric breakdown in the transformer. The risk of bubbling increases also with the content of moisture in the cellulose insulation. The cellulose acts as a kind of reservoir for the moisture).

The ratio of back-up loading over the preceding undisturbed loading is in many cases larger than the ratio of permissible overload above rated load. This means that the spare capacity requirement, if applied, restricts maximum undisturbed loading to below rated power in many typical applications.

Take as an example a case where two equal transformers are working in parallel, and one of them falls out. The permissible overload is, say 40%. This would mean that the installation is at its safety limit when each of the two units reaches 70% loading, and consequently draw about 50% of reference loss. Higher loading than 70 % of each transformer would mean more than 140 % loading of the remaining transformer if one of them falls out.

Several parameters influence the capitalised loss values. Some of these parameters must be predicted for a number of future years. Consequently such predictions are subject to considerable uncertainty.

Nevertheless, an attempt to analyse the situation to obtain reasonably relevant capitalised loss figures will most likely lead to a more economic choice of transformer than neglecting the cost of the losses completely and just go for the lowest purchase price.

Relevant parameters

- a) energy cost and how this evolves during the years the transformer will be in operation;

The energy cost per kWh is influenced by many factors, like fuel market price, supply and demand of electricity, taxes, inflation, political situations and decisions, climatic variations etc. It may increase or decrease from one year to another and may even fluctuate during the 24-hour day. This makes a fine-tuned prediction of the evolution of the energy costs impossible. In a perspective of a series of years, the energy costs will probably increase. As an approximation the evolution of energy costs can be calculated by means of an average increase rate per year. In a calculation model for the capitalised costs of the losses, it is then possible to calculate several alternative increase rates in order to see how the final result is influenced.

- b) the loading pattern of the transformer;

The loading pattern may vary much from one transformer to another. In industrial applications like for example aluminium electrolysis the transformers will be fully loaded from the beginning and will run so continuously except for shut-down periods of the pot-line due to maintenance, low aluminium prices due to market saturation or other reasons.

Transformers for operation in systems for general electricity supply to society normally have a power rating which is considerably higher than the load just after installation, in order to meet future needs and possible disturbance situations. The initial load may then be even below one half the power rating of the transformer. This means that the load loss is below one fourth of the reference loss. The low loading might prevail for several years before the load current slowly approaches the nominal current of the transformer, if the need for spare capacity permits that high loading. The capitalised load loss for a transformer with such a loading pattern will naturally be significantly lower than for a transformer where the load current is equal to the nominal current just after energising the transformer.

- c) the time horizon;

Numerous transformers are operating satisfactorily after more than half a century in service. The considerable accumulated saving potential during this long time should make an investment to achieve low transformer losses quite attractive. The amount of money the purchaser/investor accepts to invest per kW reduced loss is, however, determined by the number of years (n) he is willing to wait until the accumulated saving equals the invested amount, possibly also adjusted according to the general inflation rate. Before these n years have elapsed there is no net revenue on the investment. The earnings are coming in the following years.

Such an investment will compete with alternative investments objects, considering profitability potential and economic risk level.

The risk level connected to adequately insured transformers for general electricity supply to highly populated urban areas is normally low, while it may be higher for industrial transformers, because the owner company might not be viable for more than relatively few years.

- d) time in de-energised condition due to maintenance or other reasons;

- e) insurance premium;

The annual insurance premium is normally a certain percentage of the acquisition cost and adds to the operational costs. It is often adjusted according to the inflation rate. However, this parameter has normally not any large influence on the capitalised loss values and may be disregarded.

- f) taxes;

The property tax is normally a certain percentage of the acquisition cost and adds also to the operational costs. Rules for depreciation for the equipment in question vary from one country to another. After a certain number of years the value of the transformer is written down, and the property tax may disappear.

- g) the cost of the losses in the feeding system (including generators, transformers, lines and cables) caused by the losses in the transformer under consideration;

- h) generation installation costs;

Investments are needed to build electric power stations with buildings, generators, turbines, nuclear reactors, cooling towers, hydro regulations with dams and tunnels and so on. For a certain invested amount a number of MW electric power has been made available.

- i) transmission installation costs;

Investments are needed to transmit the electric power from the power station to the terminals of the transformer under consideration.

- j) cost for the energy consumed by the cooling equipment (fans and pumps). Separate capitalised values for power needed for the cooling equipment is sometimes specified;

Parameters g), h) and i) are in the following text assumed to be included in the kWh-price (d) at the primary terminals of the transformer in question.

Capitalisation of no load loss

The wanted figure is the maximum amount of money (X) the purchaser is willing to invest in order to reduce the transformer no load loss by 1 kW.

[Readers wishing to use the loss capitalisation formulas without going through the background and the development of the formulas, can go to equations (4-14) and (4-28) for no-load losses and load losses respectively.]

Assume as an example a transformer purchaser who buys the electric energy from a utility at the primary terminals of the transformer at a price of d \$/kWh. The price d is assumed to cover all the costs to generate 1 kWh and transmit this energy from the generator terminals to the point in the system where the transformer is situated, including the losses in the generator and the feeding transmission system. d is intended to be a representative constant value for the variable energy price during the *first* year of transformer operation. The energy cost for 1 kW the first year will then be 8760·d \$, provided the power is consumed continuously during all the 8760 hours of the whole year.

Assume that the energy price increases p% per year as an average for a number of n years. The energy cost for 1 kW during the second year of operation will then be:

$$8760 \cdot d \cdot \left(1 + \frac{p}{100}\right) \quad (4-1)$$

For the third year:

$$8760 \cdot d \cdot \left(1 + \frac{p}{100}\right)^2 \quad (4-2)$$

For the nth year:

$$8760 \cdot d \cdot \left(1 + \frac{p}{100}\right)^{n-1} \quad (4-3)$$

Setting:

$$q = 1 + \frac{p}{100} \quad (4-4)$$

the sum of the energy cost for

consuming 1 kW continuously during n years becomes:

$$8760 \cdot d \cdot (1 + q + q^2 + \dots + q^{n-1}) \quad (4-5)$$

where the expression within the

brackets is a geometric series with the quotient q. The sum s of this series is:

$$s = \frac{q^n - 1}{q - 1} \quad (4-6)$$

To calculate the total cost for 1 kW during n years the cost for the first year 8760·d must then be multiplied with the factor s.

The diagram in Figure 4-3 illustrates how this factor varies with p and n.

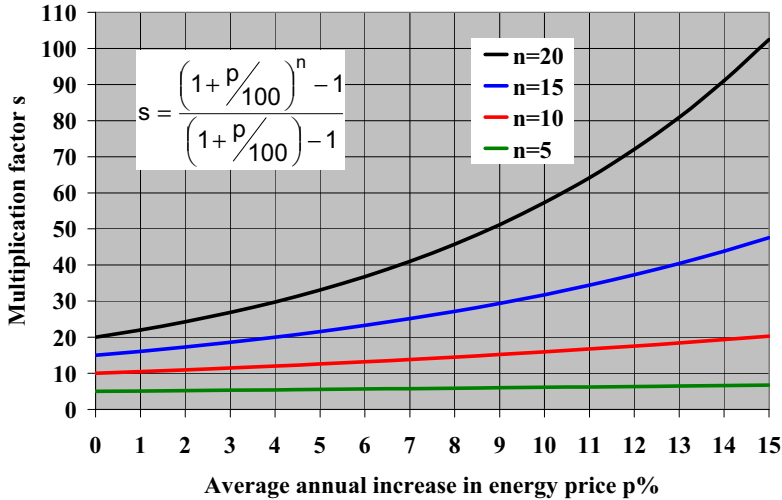


Figure 4-3

For example, the accumulated cost of 1 kW no load loss after 20 years is 41 times the cost of the first year if the average annual increase in the energy price is 7%.

The diagram in Figure 4-4 shows the multiplication factor for the whole physical lifetime of the transformer (say $n=50$ years) versus the average annual increase in energy price. It indicates that during the lifetime of a transformer the saving potential by lowering the transformer loss might be quite considerable.

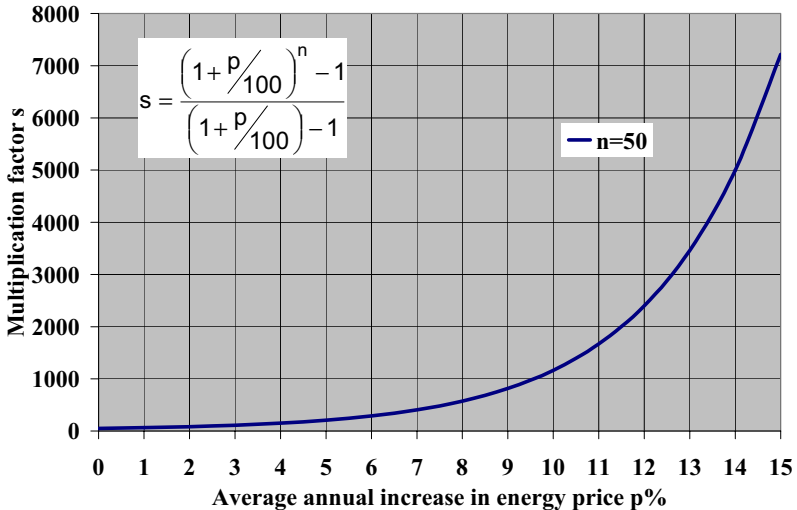


Figure 4-4

At an average annual increase rate of for example 7%, the savings during the lifetime of the transformer for 1 kW lower no load loss would be more than 400 times the energy cost for 1 kW no load loss the first year in operation.

How much should a purchaser/investor be recommended to pay for 1kW reduced no load loss, considering that the return on the investments has the form of avoided expenditure during the years the transformer will be in operation?

The first step to find an answer is that the purchaser should determine how many years that are allowed to elapse before the accumulated saving equals the invested amount of money. Or in other words, decide how many years (n) are allowed to elapse before the investor has got the invested amount back in the form of avoided expenditure. The investor might also require the invested amount back adjusted for an estimated average annual inflation rate of i% during the n years.

When n and i are determined, a corresponding average annual interest rate a% can be calculated as shown in the following.

The annual return of an invested amount X is:

$$X \cdot \frac{a}{100} \quad (4-7)$$

For n years this sums up to:

$$n \cdot X \cdot \frac{a}{100} \quad (4-8)$$

With an average annual inflation rate of i%, the invested amount X must after n years be adjusted to:

$$X \cdot \left(1 + \frac{i}{100}\right)^n \quad (4-9)$$

to maintain the original real value of X.

The following equation can then be set up:

$$n \cdot X \cdot \frac{a}{100} = X \cdot \left(1 + \frac{i}{100}\right)^n \quad (4-10)$$

This equation gives the correlation between the three variables n, i and a.

$$a = \frac{100}{n} \cdot \left(1 + \frac{i}{100}\right)^n \quad (4-11)$$

The total return on the invested amount X to obtain 1 kW less no load loss should be equal to the reduced *energy* cost for 1 kW less no load loss *accumulated* during n years of operation:

$$8760 \cdot d \cdot \frac{\left(1 + \frac{p}{100}\right)^n - 1}{\left(1 + \frac{p}{100}\right) - 1} \quad (4-12)$$

The following basic equation can then be written:

$$n \cdot X \cdot \frac{a}{100} = 8760 \cdot d \cdot \frac{\left(1 + \frac{p}{100}\right)^n - 1}{\left(1 + \frac{p}{100}\right) - 1} \quad (4-13)$$

The expression on the left side of the equal sign in (4-13) represents the return requirement on the investment X. The right side represents the economic value of the energy saving.

It follows that:

$$X = \frac{8760 \cdot d \cdot \left(\left(1 + \frac{p}{100} \right)^n - 1 \right)}{n \cdot a \cdot p} \cdot 100 \cdot 100 \quad (4-14)$$

To calculate an example with figures:

Average energy cost rate the first year of operation	$d = 0,085 \text{ \$/kWh}$
Average annual increase in energy cost rate	$p = 7 \%$
Number of years before invested amount shall be paid back	$n = 5$
Average annual general inflation rate	$i = 4 \%$
Annual interest rate on invested amount X acc. to (10)	$a = 24,33 \%$

Inserted in equation (4-14) gives:

$$X = 3520 \text{ \$/kW}$$

If the number of years n is changed to 8 and the other free variables d , p and i remain unchanged (observe that a is a dependent variable of i and n), the result will be:

$$X = 5580 \text{ \$/kW}$$

Increasing the number of years the investor allows to elapse before the invested amount is saved from 5 to 8, increases the capitalised loss value by more than 2000 \\$/kW.

An additional parameter could be added. If the transformer is not energised continuously during the year but a little less due to maintenance in the system or disturbance. Say for example the transformer is only energised 95% of the time, the 8760 hours must be multiplied by 0,95. The capitalised loss value will be reduced by the same factor.

Capitalisation of load loss

The no load loss is constant when the transformer is energised and is practically independent of the loading of the transformer. The energy consumption during a year due to the no load loss in the transformer is then simply the constant no load loss multiplied with the number of hours in a year the transformer is energised.

Contrary to the no load loss the load loss varies with the square of the instantaneous loading current, which may vary within a large range. The energy consumption during a year due to the load loss in the transformer is the sum of energy consumed within a high number of small time intervals Δt of the whole year. Assume that these time intervals are so small that the instantaneous loading current I_i can be regarded as constant within each interval. The energy consumption within such an interval will then be

$$\text{constant} \cdot I_i^2 \Delta t \quad (4-15)$$

The energy consumption for a whole year is the sum

$$\text{constant} \cdot \sum I_i^2 \Delta t \quad (4-16)$$

Introduce now a parameter called the equivalent loading current I_{eq} . That is a constant loading current that consumes the same amount of energy during the 8760 hours of a year as according to expression (4-16).

$$I_{eq}^2 = \frac{\sum I_i^2 \cdot \Delta t}{8760} \quad (4-17)$$

The load loss is proportional to the square of I_{eq}/I_N . In the following I_{eq} will be expressed in p.u. of the nominal current I_N of the transformer. The load loss is then proportional to the square of I_{eq} .

The target is to find capitalised value for the load loss. One question is how much are the savings of 1 kW reduced reference load loss (referred to nominal current I_N and reference temperature) accumulated over a certain number of years?

To answer this a couple of more variables must be taken into consideration:

the equivalent loading current the first year in operation I_{eqinit}

the annual average increase in the equivalent loading current z %

The average energy price the first year in operation is d \$/kWh and the average annual increase in the energy price is p %, as for the no load loss.

The savings for 1 kW less reference load loss the first year in operation is

$$I_{eqinit}^2 \cdot 8760 \cdot d \quad (4-18)$$

For the second year

$$I_{eqinit}^2 \cdot \left(1 + \frac{z}{100}\right)^2 \cdot 8760 \cdot d \cdot \left(1 + \frac{p}{100}\right) \quad (4-19)$$

For the third year

$$I_{eqinit}^2 \cdot \left[\left(1 + \frac{z}{100}\right)^2\right]^2 \cdot 8760 \cdot d \cdot \left(1 + \frac{p}{100}\right)^2 \quad (4-20)$$

For the fourth year

$$I_{eqinit}^2 \cdot \left[\left(1 + \frac{z}{100}\right)^2\right]^3 \cdot 8760 \cdot d \cdot \left(1 + \frac{p}{100}\right)^3 \quad (4-21)$$

For the n^{th} year

$$I_{eqinit}^2 \cdot \left[\left(1 + \frac{z}{100}\right)^2\right]^{n-1} \cdot 8760 \cdot d \cdot \left(1 + \frac{p}{100}\right)^{n-1} \quad (4-22)$$

The sum of the savings for n years becomes

$$I_{eqinit}^2 \cdot 8760 \cdot d \cdot \left[\begin{aligned} &1 + \left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right) + \left[\left(1 + \frac{z}{100}\right)^2\right]^2 \cdot \left(1 + \frac{p}{100}\right)^2 + \dots \\ &+ \left[\left(1 + \frac{z}{100}\right)^2\right]^{n-1} \cdot \left(1 + \frac{p}{100}\right)^{n-1} \end{aligned} \right] \quad (4-23)$$

The expression within the main brackets is a geometric series with the quotient

$$q = \left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right) \quad (4-24)$$

and the sum

$$s_n = \frac{q^n - 1}{q - 1} = \frac{\left[\left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right)\right]^n - 1}{\left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right) - 1} \quad (4-25)$$

In a shorter expression than (4-23) the accumulated savings during n years for 1 kW reduced load loss become

$$I_{eqinit}^2 \cdot 8760 \cdot d \cdot \frac{\left[\left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right)\right]^n - 1}{\left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right) - 1} \quad (4-26)$$

Analogous to the expressions (4-7) - (4-13) we can set up the following equation

$$n \cdot Y \cdot \frac{a}{100} = I_{eqinit}^2 \cdot 8760 \cdot d \cdot \frac{\left[\left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right) \right]^n - 1}{\left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right) - 1} \quad (4-27)$$

where Y is the amount invested to reduce the reference load loss 1 kW. Y can be obtained from equation (4-27).

$$Y = \frac{I_{eqinit}^2 \cdot 8760 \cdot d}{n \cdot a} \cdot \frac{\left[\left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right) \right]^n - 1}{\left(1 + \frac{z}{100}\right)^2 \cdot \left(1 + \frac{p}{100}\right) - 1} \cdot 100 \quad (4-28)$$

Numerical examples:

Assume:

$I_{eqinit} = 0,4$ in p.u. of the nominal current of the transformer

The average energy price the first year in operation

$d = 0,085$ \$/kWh

The average increase in loading current per year

$z = 5$ %

The average annual increase in energy cost rate

$p = 7$ %

The average annual inflation rate

$i = 4$ %

Number of years before the invested amount shall be paid back

$n = 5$

Annual interest rate on invested amount Y acc.to (4-11)

$a = 24,33$ %

Result:

$$Y = 700 \text{ $/kW}$$

If the number of years $n = 8$, and the other free variables d , z , p and i remain unchanged, (observe that a is a dependent variable of i and n), the result becomes:

$$Y = 1330 \text{ $/kW}$$

Capitalisation of auxiliary power consumed in the cooling equipment

Some purchasers want to evaluate the power of fans and pumps belonging to the cooling equipment as well. This must also be based on certain assumptions.

For example if the fans and pumps must run even when the transformer is unloaded but energised, the capitalised auxiliary loss will in principle be the same as the capitalised no load loss. However, the energy price d \$/kWh might be different at the low voltage level of the fan and pump motors, and the capitalisation value must be adjusted accordingly.

For larger power transformers the cooling equipment may consist of several sections. For example two sections, where one section provides sufficient cooling up to 70% load, and the other section is running only when the load exceeds 70%. In such a case two capitalisation values apply, one for the first section and one for the second. The reason is that the second section probably will be running a less number of hours than the first section. It may even last several years after installation before the transformer loading makes it necessary to run both sections.

If n (the number of years the investor is willing to wait before he has got back the invested amount to reduce the power in the second section by 1kW) is for example 5, and the second section will not be in operation at all the first 5 years after the transformer installation, the capitalised loss for the second section will be zero.

Take as another example that the second section is in operation 1000 hours each year the first n years, the basic equation (4-13) still apply with the exception that the number 8760 must be replaced by 1000.

If the number of operational hours is estimated to vary from one year to another, the right side of (4-13) can be split into several year-by-year terms.

Comments:

- The earnings of investment in lower transformer losses have the form of avoidance of future expenses. The accumulated avoided expenditure increases during the whole time the transformer is in operation. The strategic key question for the purchaser/investor is how many years he is prepared to wait before the avoided expenditure equals the invested amount (possibly adjusted for the general inflation) in lower losses at the time of purchase. In other words the choice of n in equations (4-14), (4-28) and (4-11).
- n is the only parameter in equations (4-14), (4-28) and (4-11) the purchaser/investor is free to choose. He can only make the best possible estimate of z , p and i (see (4-11)), but has no influence on their future real numerical values.
- n and d are the two parameters that have the largest influence on the capitalised values.
- p and i influences respectively the right and the left side of (4-13) in the same direction. p and i tend to follow each other. For these reasons p and i have only a moderate influence on the capitalised loss values. However, it is not unreasonable to assume that the increase rate of energy cost (p) will be higher than the general inflation rate (i). The present calculation method offers the opportunity to distinguish between the two.
- The uncertainty in the estimation of the parameters z , p and i increases the further into the future one goes (high n), which in turn influences the relevance of the capitalised loss values.
- For air-cooled transformers situated in-door and for water-cooled transformers the provision of sufficient quantity of cooling air or water may involve costs. Such costs, expressed in terms of $\$/kW$ (or any other currency that is used for d), should be added to the capitalised loss values obtained from equation (4-14) and (4-28).
- The sum of the manufacturing costs and the economic value of the total transformer losses is called the comparison price. The aim of the transformer optimisation is to obtain a transformer with dimensions and losses that gives the minimum comparison price. Investigations show that the comparison price of transformers that are optimised with capitalised loss values that lie within $\pm 30 - 40\%$ of a "correct" value does not increase the comparison price by more than about 1%. Consequently, the total economy of the installation is not critically dependent on a very accurate forecast of correct capitalised loss values. But totally unrealistic values should be avoided.
- On a long-term base investment in lower losses is very profitable. In addition investment in lower losses in a transformer installed to day contributes to less energy consumption in the society in the future and to better environment.
- Finally another parameter associated with the transformer efficiency is the short circuit impedance of the transformer, which causes a voltage drop on the secondary side when the transformer is loaded. A high short-circuit impedance causes a high voltage drop and a lower power supplied to the secondary system. See section 11.5 page 138.

On the other hand low short circuit impedance will increase the short circuit current through the windings in case of a short circuit on the secondary side. The mechanical forces on the windings increase with the square of the short circuit current, and it may become necessary to increase the cross section of the winding conductors in order to enable the windings to withstand the forces. In turn this will increase the dimensions and the weight of the transformer and consequently the manufacturing cost.

The choice of short circuit impedance will be a compromise between the two aspects voltage drop and the forces acting on the windings during short circuit current. The purchaser may also desire to use the short circuit impedance of the transformer as a short circuit current limiting device to protect equipment in the system on the secondary side.

Providing the transformer with a regulating winding and a tap changer can compensate the voltage drop in the transformer. Installing compensating capacitors in the system is an alternative.

5. INFORMATION REQUIRED WITH ENQUIRY AND ORDER

For application for quotations and possible ordering transformers, contact your nearest ABB office or search for your product and ABB contact on <http://www.abb.com>

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The list is not exhausted, but can in any case be used as a checklist.

5.1. NORMAL INFORMATION

The following information shall be given in all cases:

- Particulars of the specifications to which the transformer shall comply.
E.g. international and national standards, local standards, regulations and particular customer requirements,
- Kind of transformer, for example: separate winding transformer, auto-transformer or booster transformer,
- Single or three-phase unit,
- Number of phases in system,
- Frequency.

E.g. in North America, parts of South-America, half of Japan, often on board ships 60 Hz is used, most other countries use 50 Hz. Other frequencies may be actual, 400 Hz on board aeroplane, 16 ⅔ Hz for railway. Continuous operation at frequency less than 95% of rated value has to be specified,

- Dry-type or liquid filled. If liquid filled, whether mineral oil or synthetic insulating liquid. If dry-type, degree of protection (see IEC 60529),

If dry type the insulation system temperature classification should be agreed. E.g. a dry-type solution may give less expensive buildings, but availability concerning power and voltage are limited. High fire point liquid based on mineral oil or other synthetic fluids as for instance dimethyl silicone fluid may give building savings,

- Indoor or outdoor type,
- Type of cooling,
Reference is made to section 7.2 page 96,
- Rated power for each winding and, for tapping range exceeding $\pm 5\%$, the specified maximum current tapping.

Recommended power ratings:

10 – 12,5 – 16 – 20 – 25 – 31,5 – 40 – 50 – 63 – 80 – 100 etc.

Often used practice is to have the same power over the whole tapping range. Reduced power of some minus tap is also common, but in any case it should be specified.

ANSI/IEEE standard require that power flow direction have to be specified.

If applicable the transformer is specified with alternative methods of cooling, the respective lower power values are to be stated together with the rated power (which refers to the most efficient cooling),

Typical specification could be 70% / 100% ONAN / ONAF, or as overload 100% / 130% ONAN / ONAF.

- Rated voltage for each winding
- For a transformer with tapplings:

Which winding is tapped,
the number of tapplings, and
the tapping range or tapping step,

Whether 'off-circuit' or 'on-load' tap-changing is required,

If the tapping range is more than $\pm 5\%$, the type of voltage variation, and the location of the maximum current tapping, if applicable, see IEC 60076 – 1 (2000-04) clause 5.4.

Normal specified type of voltage variation is CFVV (constant flux voltage variation) and in special cases VFVV (variable flux voltage variation). But normal operation will often be CbVV (combined voltage variation).

- Highest voltage for equipment (U_m) for each winding (with respect to insulation, see IEC 60076-3),

U_m according standard voltage levels. Specified voltage in some tap changer plus positions may be higher than U_m (Maximum system voltage). But continuous operation at voltage above U_m has to be specified.

- Method of system earthing (for each winding),
- Insulation level (see IEC 60076-3), for each winding,
Unusual voltage condition including transient over voltages, resonance, switching surges etc., which may require special insulation design has to be considered.
- Connection symbol and neutral terminals, if required for any winding,
If already a connection between different voltage systems exists in the network it is mandatory to specify appropriate connection symbol. In connection symbol YNyn0 the letters "N" and "n" means neutral points accessible on external terminals.
- Any peculiarities of installation, assembly, transport and handling. Restrictions on dimensions and mass,
In areas with unknown infrastructure it is mandatory to clarify at an early stage handling, transport- and lifting possibilities and limitations.
- Details of auxiliary supply voltage (for fans and pumps, tap-changer, alarms etc),
- Fittings required and an indication of the side from which meters, rating plates, oil-level indicators, etc., shall be legible,
- Type of oil preservation system,
See 7.4.1.5 page 105. Oil preservation systems.
- For multi-winding transformers, required power-loading combinations, stating, when necessary, the active and reactive outputs separately, especially in the case of multi-winding auto-transformers.

Capitalisation of losses, see section 4 page 62.

5.2. SPECIAL INFORMATION

The following additional information may need to be given:

- If a lightning impulse voltage test is required, whether or not the test is to include chopped waves (see IEC 60076-3),
In IEC standard LIC (lightning impulse chopped on tail) is a special test. In ANSI/IEEE standard LIC is part of normal LI test procedure. Some national standards influenced by ANSI/IEEE have adopted LIC as part of LI test even if they mainly stick to IEC.
- Whether a stabilizing winding is required and, if so, the method of earthing,
If neutral point in a star connected winding is not isolated, it can be loaded and the zero sequence current has to be compensated in a delta-connected winding. In transformer with 5-leg core a delta-connected winding is needed to limit the zero sequence impedance. See also section 11.
- Short-circuit impedance, or impedance range (see IEC 60076-1 Annex C). For multi-winding transformers, any impedance's that are specified for particular pairs of windings (together with relevant reference ratings if percentage values are given),
The transformer impedance limits the dimensioning short circuit power in the secondary network. On the other hand high short circuit impedance reduces the transformer efficiency.
- Tolerances on voltage ratios and short-circuit impedance's as left to agreement in IEC 60076-1 Table 1, or deviating from values given in the table,
The requirement regarding voltage ratio according to Table 1 is $\pm 0.5\%$ on principal tap, other taps according to agreement, but most transformer suppliers normally fulfils the requirement of $\pm 0.5\%$ on all taps.
- Whether a generator transformer is to be connected to the generator directly or switchgear, and whether it will be subjected to load rejection conditions,
Which can give up to 1.4 times normal voltage in 5 seconds.
- Whether a transformer is to be connected directly or by a short length of overhead line to gas-insulated switchgear (GIS).
Also connection of large power transformer with high current isolated phase bus duct has to be mentioned,
- Altitude above sea level, if in excess of 1 000 m (3 300 ft),

- Special ambient temperature conditions, (see IEC 60076-1 section 1.2 b)), or restrictions to circulation of cooling air.

In addition for example limitations in oil and winding temperature rises (e.g. 55/50 instead of 65/60 °C) may be given.

The ambient conditions, for instance semi indoor arrangement or tropical installation, must be considered and specified temperature rise adjusted accordingly.

When water-cooled transformer, if temperature of cooling water is outside standard condition.

Also other special ambient conditions as damaging fumes or vapours, excessive or abrasive dust, explosive mixtures of dust or gases, steam, salt spray excessive moisture, dripping water or harsh environments as coastal or duty has to be mentioned.

- Expected seismic activity at the installation site which requires special consideration, See also section 6.4 page 91.
Be also aware of other caused vibration, tilting, shock, etc.
- Special installation space restrictions which may influence the insulation clearances and terminal locations on the transformer, *also the maintenance*
- Whether load current wave shape will be heavily distorted. Whether unbalanced phase loading is anticipated. In both cases, details to be given.
Load with abnormal harmonics current, harmonic factor above 5%, may cause excessive losses and abnormal heating.
Other special operation conditions such as:
Continuous load operation at voltage and voltage per Hertz above 105% of rated values, and above 110% in no-load condition.
Continuous operation at load power factor less than 80%,
- Whether transformers will be subjected to frequent over-currents, for example, furnace transformers and traction feeding transformers, *and other impact duty such as chipper mill in timber handling etc. and also heavy capacitive motor duty,*
- Details of intended regular cyclic overloading other than covered by IEC 60076 – 1 (2000-04) clause 4.2 (to enable the rating of the transformer auxiliary equipment to be established),
- Any other exceptional service conditions.
Unusual strong magnetic fields,
- If a transformer has alternative winding connections, how they should be changed, and which connection is required ex works
- Short-circuit characteristics of the connected systems (expressed as short-circuit power or current, or system impedance data) and possible limitations affecting the transformer design (see IEC 60076-5),
Unusual short-circuit application condition and planned short circuits as part of regular operation or relaying practice.
- Whether sound-level measurement is to be carried out (see IEC 60551),
The sound level can be given as sound pressure or as sound power, normally A-weighted, see 11.11 page 153.
- Vacuum withstand of the transformer tank and, possibly, the conservator, if a specific value is required.
It is recommended to specify both tank and conservator to sustain full vacuum for larger units. This allows oil filling under vacuum at site.
- Any tests not referred to above which may be required.

This should be mentioned separately and may lead to additional cost and longer delivery time.

Any information regarding the required corrosion resistance of the surface treatment in reference to the geographic zone and pollution zone has to be stated.

5.3. PARALLEL OPERATIONS

If parallel operation with existing transformers is required, this shall be stated and the following information on the existing transformers given:

- Rated power,
- Rated voltage ratio,
- Voltage ratios corresponding to tapings other than the principal tapping,
- Load loss at rated current on the principal tapping, corrected to the appropriate reference temperature,
- Short-circuit impedance on the principal tapping and at least on the extreme tapings, if the tapping range of the tapped winding exceeds $\pm 5\%$,
- Diagram of connections, or connection symbol, or both.

NOTE: On multi-winding transformers, supplementary information will generally be required.

6. TRANSFORMER DESIGN

This chapter gives a little more detailed description of the main parts of the transformer. The active part where the transformation takes place consists of the core and the windings.

6.1. CORES

This section describes various types of cores. The core material is described in section 13.1 page 159.

Figure 6-1 shows a three-phase core with three limbs, which are magnetically connected with each other at the upper and lower ends by yokes. The space available for the windings is called the window. Normally the limbs are arranged in one plane and with vertical orientation.

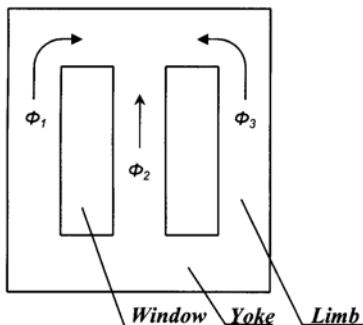


Figure 6-1

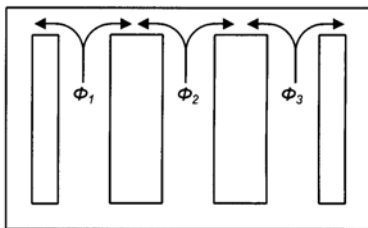


Figure 6-2

In three-phase transformers all the windings for each phase are located on their own limb. The three limbs are magnetically coupled together by the upper and lower yokes. In normal symmetric operation the sum of the voltages and the sum of the currents are at any instant equal to zero. The sum of the fluxes in the three limbs is also equal to zero. All the flux will remain in the core when the three limbs are connected together at the upper and lower ends. The flux within the limb varies sinusoidally, like the voltage. In the yoke the flux divides and has in a three-limb core its return path in the two other limbs. See Figure 6-1.

In a three-phase three-limb core the yokes must be able to carry the same flux as in the limbs. In practice the cross section of the yokes is the same as of the limbs or somewhat larger.

In three-phase five-limb cores the flux from the three main limbs with windings have additional return paths through the two outer side limbs. This means that the main flux divides when it comes to the yoke. See Figure 6-2. The yokes and the side limbs can then be dimensioned for one half of the main flux. In other words, the cross section of the yokes and the side limbs is one half of the cross section of the main limbs. In turn this gives the designer the possibility to reduce the total height of the core and the transport height, while the limb height and the space of the window may remain the same as in a three-limb core.

A five-limb core is more expensive than a three-limb core, so the latter is the preferred choice as far as the transport profile permits.

From an operational point of view users should be aware that five-limb transformers have extremely high zero sequence impedance (like shell-type transformers) unless a delta connected winding is provided.

Another possibility to cope with transport profile or transport weight restrictions is to make three single-phase transformers instead of one three-phase transformer. The core for single-phase transformers can be made in two different ways, either with one mid-limb with windings and two side-limbs for the return of the flux or with two limbs with windings. See Figure 6-3 and Figure 6-4.

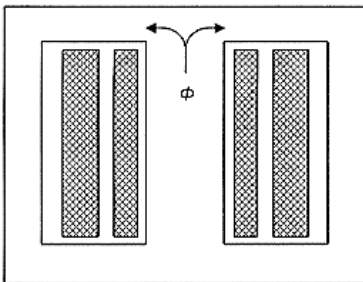


Figure 6-3

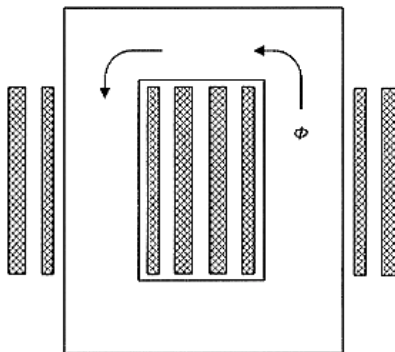


Figure 6-4

The design in Figure 6-3 is in general more economical than that in Figure 6-4. However, in certain cases, for example when two generators are feeding one transformer, the two limb design may be preferred because it is quite convenient to let one generator feed the low voltage winding on one limb and the other generator feed the winding on the other limb.

Another advantage with single-phase transformers is that a single-phase stand-by spare unit is cheaper than a three-phase one.

Sometimes the power rating of the transformer is so high that although the power rating is shared among three single-phase transformers the single-phase windings must be placed on two wound limbs of the single-phase core. A core steel frame consisting of two unwound side limbs and the yokes with a cross section of half the cross section of the wound limbs must be provided in order to keep the transformer height within the permitted transport profile. Figure 6-5 shows an example on such a core.

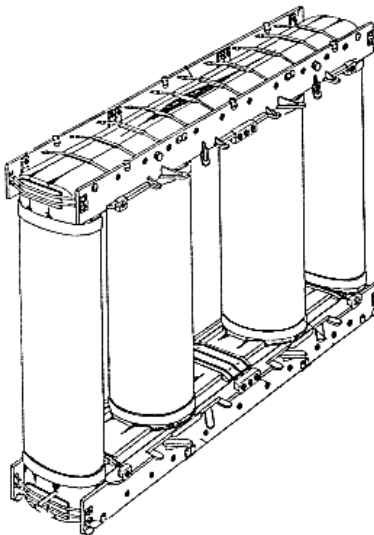
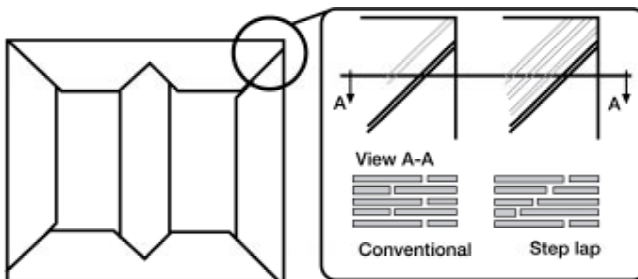


Figure 6-5

The shape of the thin (a few tenths of a millimetre) sheets has been designed to achieve low losses and low magnetising current. The connection between limb and yoke is arranged as 45 degrees mitred joints in order to achieve a large crossover section and low flux density where the magnetic flux does not proceed in a preferred direction. The sheets are laid in packets of two or four sheets where each packet has the joint displaced relative to the adjacent packet. Such an overlapping gives a rigid mechanical structure of the core together with a reduction of the fringe effect for the flux traversing the joint.



General stacking pattern for a three-phase three limb core with conventional or step-lap joints.

Figure 6-6

In recent years the step-lap joint has been most applied. By making a stepwise shift of the joints it is possible to reduce the magnetisation losses still further in the joints between the limbs and the yokes. The two jointing methods are illustrated in Figure 6-6.

Generally the core laminations are insulated from earth and deliberately earthed in one point only. It is then possible to reveal any unintentional earthing, which may give rise to circulating currents if more than one point of the core has connection to earth. In customer specifications there is often a clause saying that the core shall be earthed in one point only and that the dielectric withstand shall be 2 kV ac.

The high number of the thin core steel sheets in the limbs is kept together by means of glue for the smaller transformers, for the larger transformers by means of steel straps around the limbs or an epoxy-cured stocking. Besides rigid mechanical properties the fabric stocking is made slightly conductive in order to reduce the electric field stress around the sharp corners on the lamination packets in the limb. Holes through the laminations are then avoided, which would disturb the magnetic flux distribution within the core and set up additional losses. Core clamps with curved tie bolts keep the yoke laminations together.

For clamping and support of the windings in their axial direction the centre portion of the yokes are made with plane surfaces in the core window. These plane surfaces are extended outside the core laminations and supported by the core clamps. On large units with high leakage flux the outer section of this plane may be covered by core steel laminations (electromagnetic winding supports).

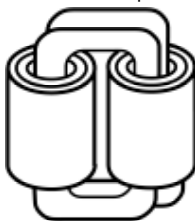


Figure 6-7

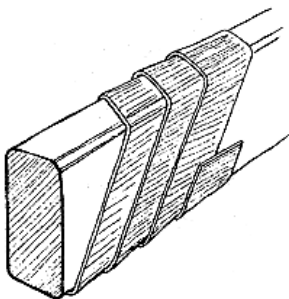
In addition to being a structural member it provides a low reluctance return path via the core for the leakage flux. In modern transformers the insulation requirement has also been extended to the core clamps.

The stacked core described in this section is the dominant type of core used in large transformers. Wound cores are used as an economical type for single-phase distribution transformers. This type is shown in Figure 6-7.

6.2. WINDINGS

The shape of the winding conductor in power transformers is usually rectangular in order to utilise the available space effectively. Even in smaller transformers for distribution purposes where the necessary conductor cross section easily can be obtained by means of a small circular wire, this wire is often flattened on two sides to increase the space factor in the core window.

With increasing conductor area the conductor must be divided into two or more parallel conductor elements in order to reduce the eddy current losses in the winding and ease the winding work. The rectangular shaped conductor element is called a strand. The word 'conductor' is then used in a more abstract sense as a composite word for 'winding current carrier'.



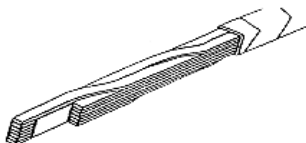
Conductor strand with insulation paper lapping

Each strand is insulated either by paper lapping or by an enamel lacquer. Two separately insulated and electrically parallel strands may sometimes have a common paper covering. The two insulated strands in a common paper covering is called a cable.

The word 'cable' is used here to denote the smallest visible conductor element when viewing the winding externally. This can be described as follows: one or several cables in parallel may carry the winding current where the cables are separately insulated. Each cable can in turn contain one or several strands in parallel.

The paper lapping is built up of thin (a few tens of micrometers) paper strips, a few centimetres wide, wound around and along the strand as indicated in Figure 6-8. The paper is lapped in several layers to obtain the necessary total thickness set by the electrical and mechanical stresses.

Figure 6-8



Continuously transposed cable

A special kind of winding conductor is the continuously transposed cable. This cable is built up of two layers of enamel lacquer insulated strands arranged axially upon each other, as shown in Figure 6-9. By transposing the outer strand of one layer to the next layer with a regular pitch and applying common outer insulation a continuous transposed cable is achieved.

When traversing the same flux for a whole transposition cycle, all strand loops receive the same induced voltage, and circulating currents between the strands are avoided.

Figure 6-9

A transposed cable may contain up to a hundred strands in parallel. With a transposition pitch of 10 cm, a full cycle is completed after some metres.

Transpositions of strands must also be made in windings with conventional conductors to avoid circulating currents. These transpositions are then made during the work in the winding machine. To make these transpositions is quite time consuming. The manufacturers of continuously transposed cables make the transpositions in an automatic machine. If necessary for increased mechanical strength the strands are covered with epoxy glue, which cures during processing the winding. For lower voltages a netting around the transposed cable is used to keep the strands together. For higher voltages insulation paper covers the cable.

In order to avoid high local dielectric stresses, the conductor surface is smooth and without scars. The corners are rounded. The conductor material is often annealed when the paper lapping starts. The material is mechanically soft. In order to withstand the short-circuit forces it is sometime necessary to increase the strength of the material by means of cold working. One way to do the cold working process is to expose the strand to a repetitive bending operation.

In large power transformers the mechanical forces during short circuit current have often more influence on the winding dimensions than thermal aspects and loss considerations.

Winding types

Windings can be divided into four main types:

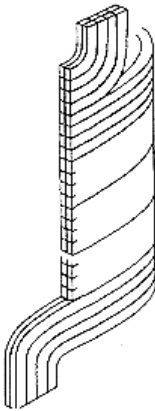
- Layer windings
- Helical windings
- Disc windings
- Foil windings

The number of turns and the current in the winding primarily determine the choice of winding type.

Layer windings

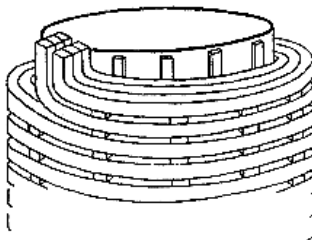
The turns are arranged axially along the winding. The consecutive turns are wound close to each other without any intermediate space. The winding may be made as a single or multilayer winding.

Within ABB single and multilayer windings are used mainly for small and medium size transformers. For large transformers this winding type is used for regulating windings. Single layer or multilayer types are used.



Regulating winding in layer type design

Figure 6-10



*Sketch of a double threaded
helical winding*

Figure 6-11

Helical windings

The helical winding can be seen as a variant of the multilayer winding but with spacers between each turn or thread in the winding. The helical winding is suitable for high currents, where the current is shared between several parallel strands. Then the dimensions of each strand can be kept reasonably small in order to keep the eddy current losses low.

All cables (one or several strands in common paper covering) in a disc belong to the same electrical turn, and they are all connected in parallel. The winding can be made as single threaded or multi threaded with two or more discs electrically in parallel.

The parallel connected winding conductors and strands are situated in a magnetic field that varies from point to point inside the volume occupied by the winding. To avoid circulating currents between the strands the position of each strand along the winding is changed in such a way along the winding that each strand encloses the same amount of magnetic field. The induced voltage in each loop formed by each strand will then be the same.

Without this precaution (called transposition of conductors and strands) the current distribution among the strands would be very uneven. Some strands would carry high currents while other strands would carry low currents. This would create unnecessary high temperature spots and increased losses.

The helical winding is the preferred concept when the number of turns and the total amount of current permit. The quantity of conducting material that can be fitted inside a given volume is high compared to other types of winding. It is said that helical windings have a high space factor, which is beneficial for an overall total mass – total loss relation. Moreover it is mechanically robust and easy to manufacture, particularly when continuously transposed cable is used.

Disc windings

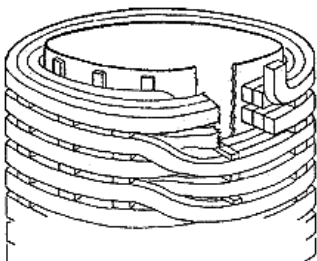
Disc windings

The disc-winding concept is used for windings with a large number of turns and relatively small currents. The disc winding is built up of a number of discs connected in series. In each disc the turns are wound in radial direction like a spiral in inwards and outwards direction in adjacent discs.

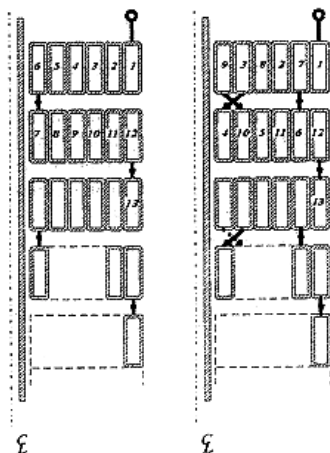
Generally disc winding will be preferred instead of helical winding when the number of turns is high. In a helical winding the height of strands will decrease by increasing number of turns. Heights below a few millimetres are not feasible. In addition the relation between the quantity of conductor and insulation becomes uneconomically low. Low strand height has also a negative impact on the mechanical strength of the winding.

The major difference between a helical and a disc winding is the number of turns per disc. In helical windings there are never more than one turn per disc while disc windings have more than one turn per disc. Disc windings offer freedom to choose the number of discs and the number of turns per disc as long as the product of the two equals the desired total number of turns.

The mechanical properties of disc windings are similar to the helical winding.



Sketch of a disc winding



Conventional and interleaved disc winding

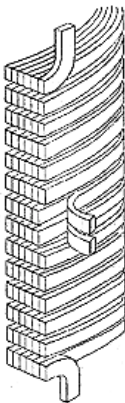
Figure 6-12

The capacitance between segments of conventional disc windings is fairly low in comparison with the capacitance between segments and earth. For fast transient voltages coming from the connected power system hitting the transformer this results in a pronounced non-linear voltage distribution within the winding and high local dielectric stresses, particularly in the beginning of the winding.

One way to alleviate this phenomenon is to interleave the turns of adjacent discs. After having passed half of the number of turns in a disc the conductor goes to the next disc and then returns to the previous disc for the remaining turns. Such an arrangement increases the capacitance along the winding (the series capacitance), which in turn gives a more linear voltage distribution along the winding during transient voltage conditions.

A major application for the disc winding is in windings for the highest voltages. These are windings where the dielectric stresses need special care. One particular item for high voltage disc windings is the location of the winding terminal.

Higher voltage systems are in most cases operated with directly earthed neutral point, which means that the system neutral is effectively tied to earth potential. With the three-phase winding connected in star (the most common connection for higher voltages) the line end is on a high potential and the neutral end close to earth potential. The winding insulation towards earth can then be built according to the actual voltage to earth in each section of the winding. The term 'non-uniform insulation' in the IEC standard means full insulation level at the line end and reduced insulation level in the neutral.



*Disk winding with
center entry*

Figure 6-13

In transformers with non-uniform insulation an economic design solution is to place the line entry at the mid of the winding height as shown in Figure 6-13. The winding has two halves with opposite winding direction, and the two halves are connected in parallel. The potential at the top and the bottom of the winding is in service close to earth potential, which means that the distances between the winding and the yokes can be smaller and the insulation system towards an adjacent winding simpler than if both ends had full insulation level.

A special kind of disc winding is the double-disc winding. This winding type is used for the highest currents, in the magnitude of 100 kA like in furnace transformers and rectifier transformers for industrial applications. The voltage is low, seldom much above 1 kV, often lower.

The winding has a number of parallel-connected groups, each group consisting of two discs connected in series. The groups are situated above each other on the limb, and they are parallel connected by means of thick bus bars oriented vertically along the winding. Because of the bus bars a double-disc winding is always the utmost winding on the limb.

Foil windings

Foil windings are made of wide copper or aluminium sheet, from some tenths of a millimetre up a few millimetres thick. The main technical advantage is that axial mechanical forces acting on the windings in the transformer during short circuit currents become insignificant because induced eddy currents in the foil weaken the radial component of the magnetic leakage field at the top and the bottom of the winding. A drawback is that these eddy currents cause additional losses in areas close to the edges of the foil. Foil windings have the other advantage that the manufacturing time is short.

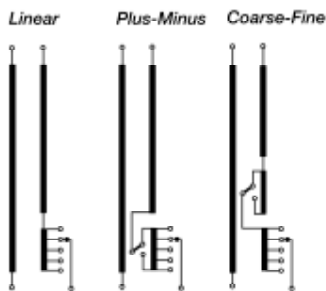
Foil windings are widely applied in low voltage windings of distribution transformers. They are also used in larger transformers and not at least in transformers that in normal service are frequently exposed to high overcurrents of short duration.

Regulating windings

Tappings for turn ratio regulation of the voltage may be provided in windings when the winding current is not too high and the regulation range is not too wide. However, if tappings are made in a disc winding, a section of the winding will be with no ampere-turns. This will disturb the ampere-turn balance with other windings in the transformer. A radial component of the magnetic flux will arise, which in turn creates enhanced axial short circuit forces. The transformer can be designed to withstand such forces provided the radial component of the magnetic field is not too large.

For larger regulating ranges the regulating turns are arranged in a separate winding shell. The height of this regulating winding is approximately the same as of the other windings. The winding type is layer or helical. The turns of each regulating step are distributed along the whole or nearly the whole winding height. The turns of each regulating step are connected in series by means of cable connections outside the winding. Cables provide connections between each regulating step and the tap changer.

The most economical design solution is to locate the regulating winding (electrically) at the neutral point of a star connected winding where the potential difference between the three phases is small. This gives the simplest and cheapest tap changer.



The three basic ways to arrange voltage regulation; linear, plus-minus and coarse-fine

Figure 6-14

Tap changers for operation during load (OLTC) as well as the cheaper type only operable in de-energised condition are available. The latter type is called off-circuit tap changer (OCTC), to emphasize that it cannot be operated when the transformer is energised. Just no current through the tap changer contacts is an insufficient condition to allow operation of an OCTC.

The tap changer and the regulating winding arrangement can be made in three different ways, either as linear, plus-minus or coarse-fine regulation. For small regulating ranges (say 10 % of nominal value) it is common to use linear regulation. This means that the voltage across the regulating winding is added to the voltage across the main winding; see the left sketch in Figure 6-14.

For larger regulating ranges a plus-minus regulation may be more suitable, see middle sketch. In a plus-minus regulation the tapped winding is connected to the main winding via a separate plus minus switch. This switch permits the voltage across the tapped winding to be added to or subtracted from the voltage across the main winding.

A third arrangement is coarse-fine regulation where the regulation function is split into two windings, one for the coarse step and one for the fine steps.

The choice of tapping arrangement affects among others:

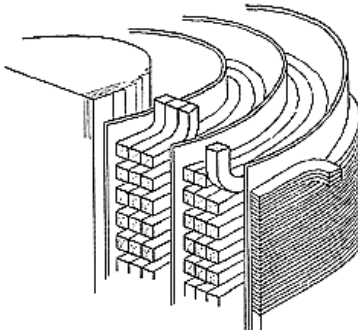
- The number of leads to the tap changer;
- The loss pattern over the tapping range;
- The relative number of turns in the main and the regulating winding.

Main insulation

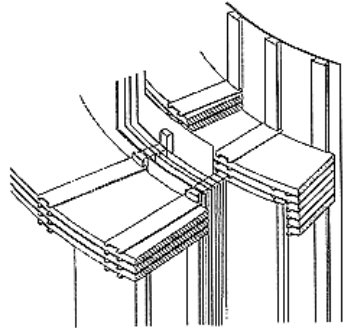
The windings are arranged as concentric shells around the core limb. They have the same approximate height and an even turn distribution along the height. Equal heights and even turn distributions are beneficial in respect of low additional losses and low short circuit stresses.

The insulation between the windings and winding to core is built as a barrier system. The insulation distance between two components of different potential (two windings or winding to core or earth) is divided into a number of segments by pressboard sheets perpendicular to the field stress. This means that the pressboard sheets should ideally be shaped along equipotential surfaces.

Vertically oriented pressboard sticks govern the distance between two adjacent barriers and thus also the windings, see Figure 6-18 and Figure 6-19.



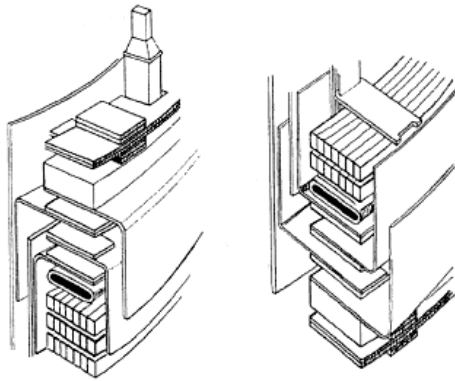
A helical winding closest to the core followed by a disc winding and a layer winding for voltage regulation.



Barrier arrangement between windings.

Figure 6-15

Windings with a high potential at their ends have the barrier system extended to cover the distance to yoke. Angle shaped pressboard elements are positioned alternately on the inside and the outside of the winding barrier system. The design provides necessary openings for the oil to enter and leave the winding, see Figure 6-16.



High voltage windings are enclosed by angle shaped barriers towards the yokes and shield rings at the winding ends for dielectric control

Figure 6-16

Figure 6-16 also shows the arrangement with shield rings. A shield ring with its large edge radii and insulation improve the stress pattern at the winding ends. In addition the shield ring increases the series capacitance of disc windings, which in turn reduces the non-linearity of the voltage distribution along the winding during transient voltage conditions and lower dielectric stresses within the winding is achieved.

The shield ring has a core of hard pressboard. A metal foil is wound around this core, but the foil does not form a closed turn. The foil is connected to a winding conductor close to the winding end. Outside the foil is a paper covering.

Cooling of windings

The windings are large heat producers, which need cooling. Oil has a high value of heat capacity: 1,8 kW/kgK (while steel and copper has 0,4 – 0,5). Its transport capacity for dissipated heat is therefore great, but there is still a need for considerable rates of oil flow through the cooling ducts in the windings.

A simple example: Suppose that 180 kW of winding losses shall be removed. The temperature difference between inlet and outlet oil may be 20 degrees. Then the necessary flow of oil is 5 kg per second ($5 \times 20 \times 1,8 = 180$). The example would be typical for a 30 – 50 MVA transformer. A large system transformer would need, say, ten times as high oil flow, that is 3 cubic meters per minute.

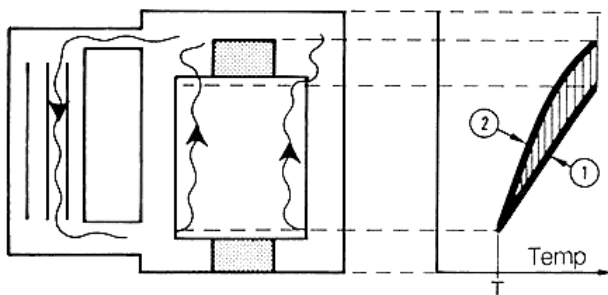


Figure 6-17

In most transformers the oil circulation through the windings is drawn automatically from the free volume in the tank by thermosiphon effect. The flow will adjust itself to an equilibrium between the thermosiphon driving head and the flow resistance in the duct. Another important physical property of the oil then appears, namely its viscosity characteristic under varying temperature.

Figure 6-17 shows a transformer with natural oil circulation. Curve 1 in the diagram to the right is the temperature profile in winding and tank. Curve 2 is the temperature profile in the radiators. The shaded area between the two curves indicates available driving head.

In hot climate this is of little concern, but in an arctic climate there may be real problems with “cold start”, that is, when a transformer has been disconnected for some time and has to be started up from a very low temperature. It may be so bad that pump motors stall. Or in a self-cooled unit the circulation between tank and radiators does not start although the temperature in the tank has gone up.

In cold climate, therefore, an oil with a lower viscosity index is usually specified. The requirements regarding viscosity are expressed in terms of a highest allowable viscosity at a specified low temperature and a highest allowable “pour point” temperature, that is, the temperature where the oil just barely flows at all.

In some countries it is tradition to design very large transformers with “forced, guided” oil flow, that is, the oil is pumped in a closed system of ducts right into the windings. The pump forces a defined and constant flow, and it is secured even with considerable flow resistance in the cooling ducts. In other countries this practice is denounced because any loss of auxiliary power would necessitate tripping of the transformer with very short notice.

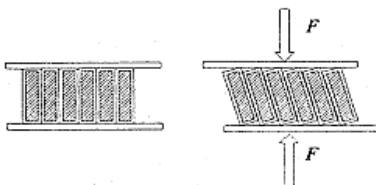
Short circuit withstand

This section describes the force pattern on and within a winding during an external short circuit. In accordance with the division of the forces into radial and axial components, withstand criteria can be established for the two directions.

The electromagnetic forces are proportional to the square of the instantaneous value of the current. With an alternating current the corresponding forces are repetitive and varying. As the current also includes a damped and decaying dc-component, the first current peak will invoke the highest electromagnetic force. In general withstand criteria are based on this first peak value of forces and currents. Under some circumstances a more complete analysis is necessary where the dynamic behaviour of the winding is considered.

In a well-balanced transformer both the inner and outer windings are subject to compressive axial forces. The radial forces tend to compress an inner winding (reduce its diameter) and expand an outer winding (increase its diameter). The forces act in such a way that they tend to increase the volume of the leakage flux space between the windings.

Permissible axial forces are limited by the mechanical strength of the winding end supports and the spacers between discs. For helical and disc windings there is an increasing probability for the conductors to tilt when increasing the axial forces.

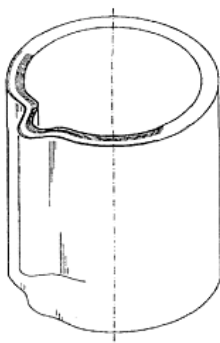


Tilting of conductors under axial stress

Small conductor dimensions in radial direction and large height in axial direction increases the risk for tilting. On the other hand a small dimension in radial direction is preferred in order to reduce the winding eddy current losses. The designer has to find a conductor dimension which gives satisfactory mechanical strength without sacrificing the requirement for low losses.

Figure 6-18

The maximum permissible radial force on an inner winding is set by the buckling strength. The failure mode can be described as a radial slide of one or several sections of the winding shell. The winding buckles. Due to the cylindrical shape of the winding the radial force cause a tangential stress in the conductor material.



Typical example on buckling of an inner winding

In order to visualise a buckling failure mode a disc section of the winding (helical or disc winding) can be represented by a number of parallel beams between two spacers. The beams are secured from twisting by the spacers, the angle between the spacer and the beam remains unchanged, but the spacer together with the beam ends are free to move axially.

With this model it can be seen that the buckling withstand increases with increasing conductor width. However, in addition other factors are important, such as the free length of the beam, that is the distance between two spacers, and the modulus of elasticity of the conductor.

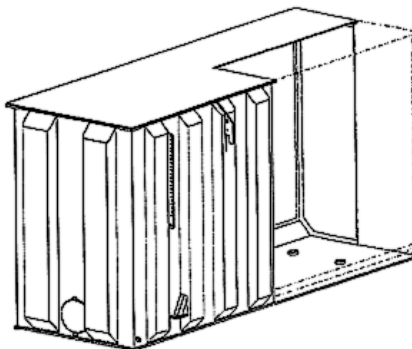
The buckling withstand is often a dimensioning factor of an inner winding and consequently of the whole transformer.

ABB's design and manufacturing practice is based upon the experience from short circuit testing of about one hundred power transformers. The service record of ABB transformers is excellent regarding their ability to withstand short circuit currents.

Figure 6-19

6.3. TANK

The tank is primarily the container for the oil and a physical protection for the active part. It also serves as support structure for accessories and control equipment.



Tank with stiffeners of box-beam design, showing jacking pad, lifting hooks and rail for transport bracket.

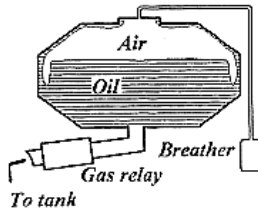
Figure 6-20

Before filling the oil the tank with the active part inside it is evacuated in order to remove all air that would endanger the dielectric strength of the transformer insulation. Consequently the tank is designed to withstand the pressure from the atmosphere with a minimum of deformations. The tightness at outside and inside overpressure is verified through suitable tests.

The cover may be bolted or welded to the tank frame. Some users prefer a bell type tank where the tank is welded or bolted to the tank bottom.

To keep the tank dimensions within the specified transport profile and, at the same time, enclose the active part in the tank in with necessary insulation clearances and still obtain a reasonably simple design often makes the designer's task a considerable challenge when designing large transformers.

Another phenomenon to take into account when designing tanks is that a coincidence of sound frequencies generated by the transformer core and the resonance frequencies of parts of the tank may enhance the sound radiated to the environment.



*Conservator with a diaphragm
between the oil and the air*

Figure 6-21

The tank is designed to permit the temperature dependent expansion of the oil. Most often a separate expansion vessel is installed, also called conservator. Since the conservator is vented to the air the oil pressure in the transformer remains fairly constant and independent of the temperature. The free access of the surrounding air is limited. Good dielectric properties of the oil require that the oil is clean and has low moisture content. Moisture in the oil will also accelerate the ageing of the cellulose insulation. Air entering the conservator is therefore filtered and dehumidified. In addition a diaphragm in form of a rubber sack that separates the oil in the conservator from the air is recommended on power transformers. See Figure 6-21.

With increasing transformer power rating the effects of large currents in and out of the transformer influence the design. The same goes for the leakage flux inside the tank. Inserts of non-magnetic material around high current bushings reduce the risk of excessive heating. Tank lining with high conductive shields expels the flux from entering the tank wall. Alternatively low reluctance material takes care of the flux before it enters into the tank wall.

6.4. EARTH QUAKE WITHSTAND ABILITY

Transformers to be installed in seismic active areas should be subject to a seismic interaction analysis.

The magnitude of the seismic load to be expected and the transformer shall withstand should be determined. A design earthquake may be set.

In certain areas there are local requirements to such analysis.

The seismic forces and the effects on the transformer, its components and the support should be evaluated. These forces interact with the other forces on the transformer, e.g. static and load forces.

In analysing the seismic behaviour, the natural frequencies, the accelerations, the forces, the displacements and the motions are determined.

A finite element method may be performed in determining the stresses in selected points on the transformer. In this analysis an approximation of the physical properties and geometry is generated. A superposition technique is used to obtain the resultant displacements, forces and accelerations for the assembly under the dynamic loading of a design earthquake.

Special consideration should be given to core and winding support, and to attached equipment as bushings, conservator, cooling equipment and accessories. Also the support and the support structure and external connections should be considered.

Some customers and local regulations require the seismic interaction analysis to be approved by an independent authority.

The customer should specify the earthquake requirements in the transformer inquiry/contract.

7. TRANSFORMER COMPONENTS

7.1. TERMINALS

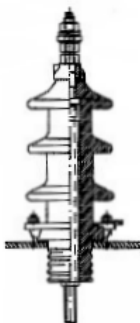
In dry-type transformers the terminals may just be ended on a terminal board in form of studs or blade connectors. The terminals may be situated inside an enclosure. In oil or liquid insulated type transformer means of bringing the electrical connection from the inside to the outside the tank has to be provided

7.1.1. Bushings

Terminals device in form of bushing brings the connection from the transformer insulation medium to the external insulation medium, which in most cases are air, but can also be oil in a cable termination box or SF6 in a gas insulated switchgear. In transformer designs with gas cushion the lower part of the bushing has to be extended to reach down into the transformer insulation medium. The bushings provide the necessary insulation between the windings electrical connection and the main tank, which is at earth potential. They provide also necessary insulation in the external medium. They need to fulfil necessary current capacity. This makes a wide range of requirements and accordingly a wide range of solutions.

The airside of an oil-to-air bushing may be done in a simpler way if only for indoor use.

7.1.1.1. Low voltage bushings

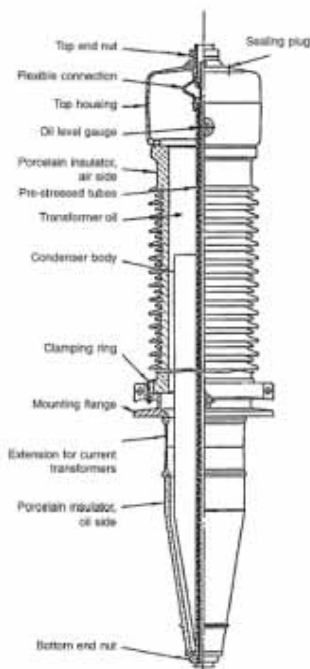


A simple low voltage oil-to-air bushing may be a rod of conducting material inserted into a porcelain tube. This has a central current-carrying bolt, usually of copper, and the insulation is provided by a combination of the porcelain shell and the transformer oil. Under oil the porcelain surface creep strength is very much greater than in air, so the oil portion of the bushing is short and has a more or less plain porcelain surface. The air portion is longer and has shed profile in order to provide a very much longer creep path, a portion of which is protected so that it remains dry in rainy or foggy conditions. There are gaskets sealing between rod and porcelain and between porcelain and tank wall to prevent oil leaks.

The normal limit for these simple porcelain bushings is up to 45 kV system voltage and current up in range of 10 kA.

Special low voltage bushings are available where extra efforts are put into the design to get very low partial discharge levels.

7.1.1.2. Condenser bushings



For bushings with higher rated voltage, that is in the region of from 25 kV to 52 kV or higher, dependent upon the design and the customer requirement it is necessary to introduce active control of voltage distribution between the central high voltage lead and the external metal mounting flange at ground potential. Such control is achieved by a capacitive voltage distribution. In a simple form the central rod or tube is wound up with paper in a number of layers and concentrically arranged conductive foils separate each layer. This arrangement is often called a condenser body bushing.

Such designs had already been developed before 1910 but were not fully utilized until 40 to 50 years later. For a long time laminates of phenolic paper were almost universally used. This material is also named Bakelite. The Bakelite bodies were mechanically strong but never completely free from shrinkage cracks in which corona developed in service. The bushings were relatively immune to this inner corona but it could in many cases no longer be tolerated when indication of partial discharges began to be used as a diagnostic tool for transformers in course of the 1960s and 1970s. The bushing technology then changed over to bodies of paper impregnated with transformer oil. This entailed a complication in that the bushings were not oil tight in the body itself. They had to be provided with a sealing porcelain shroud below the mounting flange on the oil side.

In the design of conventional condenser bushing the condenser body is wound on a central tube, which may be current conducting. If possible the body is coiled up from full width paper, otherwise narrow strips will be

wound in overlap from end to end. At regular intervals equalisation plates are constructed using either aluminium foil inserts or conductive ink fused to the fibres of the paper to create concentric cylinders. The lengths of these equalisation plates are stepped. The capacitance between consecutive layers is equalized, as layers with higher diameter are of shorter length. The outside of the body has a finalizing conductive layer, which is connected to the mounting flange through a jumper. This connection may be opened so that a capacitor or some other element may be inserted between the outer foil and the ground for the purpose of measurement or protection. The body is positioned in the earthed flange and inside a weatherproof insulator that can be in two parts, an upper part made of porcelain or silicone polymer with sheds and a lower part, normally under oil, made of porcelain or epoxy resin. In case the airside and oil side porcelains are compressed axially with sealing gaskets towards the mounting flange and towards the bottom and top armatures. The assembling pressure is sustained by springs allowing expansion and contraction of different components during temperature changes. The inside of the bushing, the volume between the central conductor and the outer casing is filled with transformer oil, separated from the transformer, and the condenser body is fully impregnated. The bushing head, or dome provides oil expansion space and may be fitted with a sight glass to give indication of the bushing oil level. The head allows space for an air or gas cushion to allow for expansion and contraction of the oil. This expansion space must be adequately sealed against the ingress of atmospheric air and hence moisture. Bushings with oil impregnated condenser body are primarily designed for installation at, or near, the vertical position. But with special precautions in the design they may be invented for even horizontal installation.

Different solutions are used to create the electrical path for the current through the bushing depending on the bushing design and the rated current needed.

The central conductor may be a copper bolt with connection terminals stud in both ends.

For higher current ratings the central conductor is a thick wall tube due to the skin effect.

The central tube in the bushing can be a thin wall metal tube not dimensioned for current carrying. The current goes through a draw lead connection consisting of a multi stranded flexible conductor joined to the terminal of the winding. This lead is drawn up through the central tube of the bushing. It is cut to the correct length and provided with a top connector that is fastened to the top of the bushing. When the transformer is shipped with bushings removed the draw lead is lowered down into the tank. An advantage is that no access to the lower end of the bushing is needed when mounting and dismounting the bushing.

If full current capacity of such bushing has to be utilized a solid rod solution is invented. This is a solid rod of copper, which mostly fills the available space in the central tube. The lower part of the rod is connected to the extended winding terminal and the upper part has a termination fitting to the top of the bushing. When mounting the bushing it is lowered over this rod. When bushing is dismounted for transportation the rod has a split facility at level of the bushing flange or tank cover.

For bushings with central tube dimensioned for current carrying ABB has developed the draw rod system used when the winding terminal is provided with a static shielding body that shall surround the bottom end of the bushing. This shield is permanently installed on the active part of the transformer and it contains a slightly movable contact stud that is permanently connected to the winding terminal. This contact stud carries a relatively light draw rod of steel extending nearly to the level of the cover. When the bushing is fitted, the bottom part of the draw rod is joined to an additional longer part that extends through the bushing. The bushing is guided along the complete rod down into the shield body and the contact stud is permanently pressed hard against the bottom end of the bushing when the draw rod is tensioned and fixed at the upper end of the bushing. The system includes springs to provide the contact pressure and device to compensate for temperature elongations.

The external connection to the bushing top is usually a straight cylindrical stud but customer's local standards may require other variants. The customer supplies special hardware armatures, which are suited to their bus bar. At high system voltages the bus bar conductor will be multiple wires or sometime horizontal aluminium tubes. Certain flexibility must be provided in the latter case in order to permit temperature variations and to relieve the bushing from short circuit power acting on the bars. The bushing shall, in principal, be completely unstressed and must not be used as support insulator to stretch up horizontal wires.

In HV condenser bushings provision can be made for accommodation of a number of toroid wound current transformers by incorporating an earth band at the oil-immersed end just below the mounting flange.

The airside of oil to air outdoors bushing is exposed to climatic influences, rain and possibly pollution with salt and dust. This is subject to specific standards requirements and type tests. The external withstand capability of the bushing is provided with the aid of sheds on the porcelain which are intended to keep protected parts of the insulation surface dry and clean. The standards mention total creeps distance, protected creep distance and the straight-line distance between top and bottom and it is to some extent up to customer to specify requirements.

Plant for high voltage DC is designed with elevated requirements on external insulation. The DC voltage will, under certain circumstances, provide an electrostatic precipitator effect resulting in much heavier pollution than will be found in plant at a comparable AC voltage.

The special demands on HVDC bushings has also lead to the introduction of bushings with reduced oil volume and the main insulation made by a combination of SF₆ gas, static shields and traditional technology.

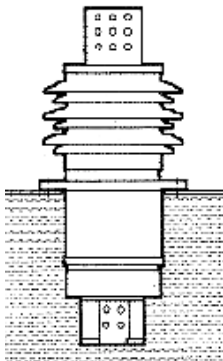
The bushing manufacturer conducts routine tests as per industry standards before delivery. Routine tests can include seal integrity, capacitance, $\tan \delta$ or power factor, power frequency and partial discharge. Limits are set by the standards based on type and rating. Type tests are required when new designs are introduced and require a series of additional tests.

A test of the external insulation of bushings is conducted under artificial rain in the laboratory with AC voltage applied for one minute, and possibly with switching impulse. Impulse tests with standard wave (1/50 μ sec) are made on the bushing in dry conditions. It is assumed that water droplets do not influence the withstand voltage values at standard impulse.

High voltage condenser bushings are available where the condenser body is made of epoxy resin vacuum impregnated paper. These bushings were originally developed for use with SF₆ but are now widely used for oil to air interfaces. These bushings for high voltage implementation are available with porcelain oil filled upper casing, but the under oil end is totally resin encapsulated. Outer housing of porcelain for outdoor bushings is still dominant due to these material excellent properties of weathering and abrasion resistance.

For medium voltages up to 145 kV total oil free design is invented. The condenser body is made of epoxy resin vacuum impregnated paper. The airside outer protective housing is made of silicone polymer moulded directly onto the condenser or it can be a hollow composite insulator, filament wound tube plus silicone, mounted outside and the gap between filled with a solid dielectric medium. The outer protection of silicone is formed with sheds. The bushing is lightweight. It can be installed in any position. For transformers exposed to earthquake or vandalism by stone throwing this may be a safer solution than porcelain.

7.1.1.3. High current bushings



Bushings for very high currents, in the range up to 30 kA, have a very large massive central conductor. Its purpose is to conduct heat. The current flows near the surface and penetrates only about 1–2 cm. The heat that is developed even at the contact surface of the airside is largely carried downward, and carried away by the top oil in the transformer.

Because of the skin effect it is advantageous to arrange at least the airside terminals on the sides of a rectangle or polygon. This collect the current from the circumference were it float and the bushing can easily be connected to a tube formed bus by sets of flexibles.

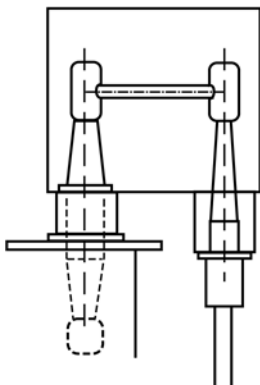
High current outlet of large transformers is often arranged as bus duct, which may give extra high temperature environment and special designed high temperature bushings have to be used.

High current terminals with low voltage on transformers for furnaces and electrolysis are not made as proper bushings but in the form of flat bar palms or cylindrical studs mounted in panels of plastic laminate.

7.1.2. Cable connections

The general design of this type of connection is that the cable is terminated in oil filled compartment according to cable manufacturer's recommendation. From there it is connected through a separable link onto an oil-to-oil bushing through the tank wall. The separating link is provided to permit disconnection of the cable from the transformer for insulation tests on the cable. It is further avoided that the inner parts of the transformer will be exposed during the time when the cable is installed, only the separate container or box involved.

Modern plastic cables for lower system voltage are usually not boxed in this manner; they are terminated in open air.



There is also a different technology with dry plug-in bushings up to 145 kV level. A conical plug is mounted on the transformer wall, and a corresponding female part is mounted on the end of the cable. When the parts are joined this provide an airtight and moisture tight bond. The components are safe to touch while live. For lower voltage level it is possible to disconnect an unloaded transformer by just pulling the plugs with an insulating rod. The insulating rod is to protect against arcing should an attempt be made to disconnect a loaded cable.

The oil to oil bushing may be omitted and the lead from the winding terminal is brought directly to the cable termination through a sufficient opening in the tank wall between the tank and cable box.

7.1.3. SF6 connections

Terminal of transformer that are directly flanged towards SF6 bus ducts have particular bushings. Insulation distances in the compressed gas atmosphere are about the same as in oil and both ends of the bushing look about the same.

Bushings for such application are today available with condenser body made of epoxy resin vacuum impregnated paper fixed in a flange. The compressed gas has an overpressure of the order of 3 atmospheres. There are multiple sealing systems between the main insulating body and the bushing-fixing flange as well as between the body and the current conductor. Within the flange between the gas side and the oil side seals, there is an annular chamber in which the gas will be trapped in case of an SF6 leakage, and from which the gas can be let out without entering the transformer. Such leakage of SF6 gas will also be detected.

Oil to SF6 bushings are also available with condenser body of oil-impregnated paper housed inside upper and lower porcelain with a metal flange between. These bushings have an oil volume separated from the transformer oil and with sealing systems towards the oil system of the transformer on one side and towards the bus bar gas enclosure on the other side. The closed oil volume of the bushing is pressure monitored so that a possible leakage from the gas system will be indicated.

7.2. COOLERS

The cooling equipment collects hot oil at the top of the tank and returns cooled oil lower down on the side. The cooling arrangement can be seen as two oil circuits with an indirect interaction, one inner and one outer circuit. The inner circuit transfers the loss energy from the heat producing surfaces to the oil. In the outer circuit the oil transfer the heat to a secondary cooling medium. The ambient air normally cools transformers.

It is possible to build air coolers with forced air circulation more compactly than cooler with natural draught. However, such a cooler also has fairly high impedance to the oil circulation in the internal circuit, which necessitates that the oil be pumped through the cooler. For built in transformers, e.g., deep underground power caverns or in some industrial application oil to water heat exchangers are used; as in such cases, sufficient air for cooling may not be available. The system also permits small physical dimensions. The disadvantage of the compact design is that auxiliary power must always be available.

Present standards give clear definitions of the different types of cooling together with special designations. The examples below are taken from IEC:

ONAN	– Oil natural	– air natural
ONAF	– Oil natural	– air forced
OFAN	– Oil forced	– air natural
OFAF	– Oil forced	– air forced
OWFW	– Oil forced	– water forced

On the oil side the oil can be directed to the heat producing surfaces by the oil pumps:

OD	– Oil directed
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A given transformer can have a combination of cooling types to permit a change in the type of cooling e.g. ONAN/ONAF etc.

Pumps as well as fans sometimes suffer breakdowns. It must be possible to exchange such components without emptying the transformer or even taking it out of service. All cooling circuits should therefore be provided with necessary valves for shutting off each separate oil circuit.

The letter O is used for mineral oil and insulating liquid with fire point ≤ 300 °C.

The letter K is used for insulating liquid with fire point > 300 °C.

The letter L is used for insulating liquid with no measurable fire point.

7.2.1. Radiators

Radiators are available in various patters. They almost consist basically of number of flat passages of edge-welded plates connecting a top and bottom header. It is possible to make the radiators slightly higher than the tank so that the top header has a swan-necked shape, this has the added benefit that it also improves the oil circulation by increasing the thermal head developed in the radiator. The radiators have a venting plug in the top header and a draining plug in the bottom header. Radiators are almost flanged direct to the transformer tank or to the headers in freestanding cooler banks through a butterfly valve permitting individual radiators to be shut off and even easily removed.

A separate, self-supporting rack, forming a freestanding cooler bank entails the cost for a separate mounting pad and fitting of the pipe work. One advantage is that the conservator may be placed on the bank. This simplifies the orientation of bushings with regard to clearances.

Because of their construction it is difficult to prepare the surface adequately and to apply paint protection to radiators under site condition. It is therefore recommended to have sheet-steel radiators hot dip galvanized.

7.2.2. Corrugated tanks

The corrugated tank is both tank and cooling surface for small and medium distribution transformers. The tank consists of cover, corrugated tank walls and bottom box.

The standard tank design is hermetically sealed type where the corrugated walls are of such a flexible construction that they expand and contract depending on the changes in the oil volume, due to temperature variations during operation. Number and depth of corrugations on each side of the tank can be optimised to meet the cooling and dynamic pressure variation requirements.

Standardised type test for hermetically sealed corrugated tank simulating the pressure variations throughout the expected service life of the transformer has been successfully performed.

Hermetically sealed transformers compared with a conservator type have several advantages. One is that the oil is not in contact with the atmosphere thus avoiding absorption of moisture from the environment another one is that it is easier to maintain (clean).



7.2.3. Fans

For larger units it is possible to suspend fans below or on the side of radiators to provide a forced draught, and achieve ONAF cooling arrangement. This might enable the transformer loading capacity to be increased by some 25%. The radiators have to be grouped in such a way to obtain coverage by the fans.

The cooling fans will generate a low frequency noise, which will be added to the noise from the transformer itself. The intensity depends on fan size, rotation speed and the design of the fan blade. Fans are available in a rich several of designs. In basic it is a standard squirrel cage motor totally enclosed with a propeller mounted direct to the shaft and in a casing provided with necessary wire guards.

Fan is also a part of a forced air heat exchanger

7.2.4. Forced oil, forced air heat exchangers

For large transformers it became very space consuming to remove the heat with natural circulation through radiators. The space requirement of compact coolers is drastically lower than for simple radiator batteries. For space reasons it may be economical to use compact coolers with appreciable flow resistance, which requires forced circulation of the oil by pumps, and strong fans for air blowing.

Such OFAF heat exchangers usually consist of round tubes with thin swaged cooling fins or elements of flat corrugated tubes. Some designs are very compact with narrow ducts on the airside and high fan pressure.

When using several coolers for OFAF cooled transformers it is preferred to arrange two or more individual coolers in series instead of parallel in order to reach a higher temperature drop. On large transformer the cooling equipment is separated into several groups or circuits, and these can be activated or deactivated as required, controlled by thermostats or may in some more advanced way.

The mounting of coolers for forced cooling with pumps and fans have several options for the orientation and grouping on the tank, depending on local conditions. In certain cases separate racks are also an option.

7.2.5. Oil-water coolers

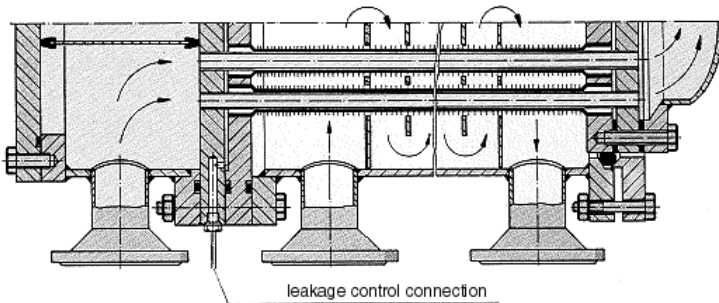
Water-cooling may be an attractive alternative when transformers are installed in a cave station, or in harsh industrial environments as steel works etc. But the choice has to be evaluated against to pump the cooling oil out in the air environment to an air cooler. An obvious risk with water-cooling in a temperate climate is freezing. In hotter climates it may more critical to have cooling water in sufficient quantities.

Water coolers are compact. They are almost conventional cylindrical tubular heat exchangers, with removable tubes. Such heat exchangers are very common and represent classical technology, and are supplied for quite many different purposes in technology. More recent designs, for instance membrane type flat heat exchangers, have hardly been used.

A central problem is the properties of the cooling water with regard to corrosion of the materials in water tubes. Leakage of water into the oil system is fatal to a transformer and such systems must be monitored with meticulous care. The installation should be arranged so that the pressure on oil side is higher than the pressure on water side, but this may not always be possible to safeguard.

Corrosion can be a problem. Cooling water analysis is recommended in order to select the most suitable materials in the cooler. Sophisticated materials, such as titanium tube coolers, may be used.

Deposition has to be avoided by ensuring that an adequate rate of water flow is maintained, but allowing this to become excessive will lead to tube erosion.



Double-tube cooler may be applied. With such an arrangement the oil and water circuits are separated by an interspace so that any fluid leakage will be collected in this space and will raise an alarm.

7.2.6. Oil pumps

Circulation pumps for oil cooling equipment are special compact, totally sealed models. The motor is immersed in the transformer oil, and there are no stuffing boxes.

The sound level of these pumps is low, compared to the transformer sound level.

7.3. VOLTAGE REGULATION EQUIPMENT

The majority of all transformers incorporate some means of adjusting their voltage ratio, by adding or removing tapping turns.

This adjustment may be made by an on-load tap-changer, or by means of an off-circuit tap-changer, or by the selection of bolted link positions with the transformer disconnected and grounded.

The degree of sophistication of the system of tap selection depends on the frequency with which it is required to change taps and the size and importance of the transformer.

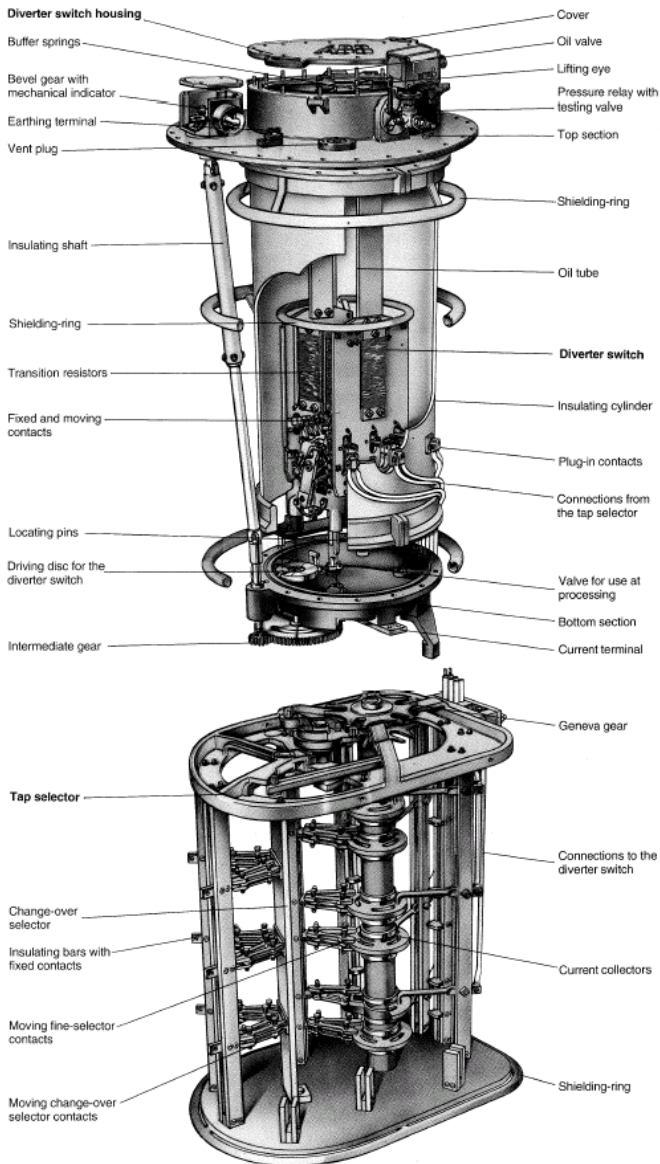
7.3.1. Off Circuit tap changers

The off-circuit tap-changer is of rather simple design, giving connection to a selected tap in the winding. As the name says it is designed only to be operated only when the transformer is de-energised.

The contact pressure may occur to be retained by some kind of spring arrangement and then some vibration is possible. In off-circuit tap-changers operating on the same tap position for years the contact resistance then may slowly increase due to local degradation and oxidation of material in the contact point. Heating will take place resulting in a build up of pyrolytic formed carbon, which will increase the contact resistance further, and also reduce the cooling. Ultimately a runaway situation is reached and the transformer will probably trip on gas actuated protection or worse; a step short circuit occurs. To avoid this it is vital that the tap changer is operated, off circuit, through its complete range a few times during regular routine maintenance to wipe the contact surfaces clean before returning it back to the selected tapping.

Of course the same advice is valid if an on-load tap-changer is left in service but without operation for a long period.

7.3.2. On load tap changers



The on-load tap-changer has to provide uninterrupted current flow during the transition operation from one tap to the other. The current flow must be maintained uninterrupted without partial short-circuiting of the tapped winding.

As early as between 1905 and 1910 arrangements were introduced for changeover between tapplings of the transformer without interruption of supply.

The operation of an on-load tap-changer can be understood by two identifiable functions. It implies a switching device that transfers the throughput power from one tap of the transformer to an adjacent one. During this operation the two taps will be connected through fitted transition impedance. In this phase the two taps will share the load current. Thereafter the connection to the former tap will be interrupted and the load has been transferred to the new tap. The device that performs this switching is called diverter switch.

The connections to the two taps that involve the diverter switch are maybe transferred one position along the series of physical taps of the regulating winding for each operation. This is the tap selector function. The tap selection is conducted without any current rupture.

A rather important improvement of tap-changers resulted from the invention of the fast acting flip-flop diverter switch, named the Jantzen principle after the inventor. The Jantzen principle imply that the switch contacts are spring-loaded and they flip over from one position to a new with only a very short interval of connection between the two taps and through transition resistor.

An alternative to the principle with fast acting switching sequence and resistors is to use reactor. In a reactor type tap-changer it is instead more difficult to break the circulating reactive current and this will rather limit step voltages but it will works well at relatively high currents. This compared to a fast operating resistance tap-changer, which can handle higher voltage but not high current. This leads to reactor tap-changer being usually located on low voltage of the transformer while resistance tap-changer will be connected on the high voltage side.

In a reactor type tap-changer the losses in the mid-point reactor due to the load current and the superimposed circulating current between the two involved tap is small and the reactor can be left permanently in circuit between them. This provide an intermediate step between two taps and this gives twice as many working positions as the number of taps in the winding.

From the 1970's tap-changers with vacuum breakers have been available. Vacuum breakers have low contact erosion and this gives tap-changers with increased number of operation between necessary services. The design is however generally becoming more complex.

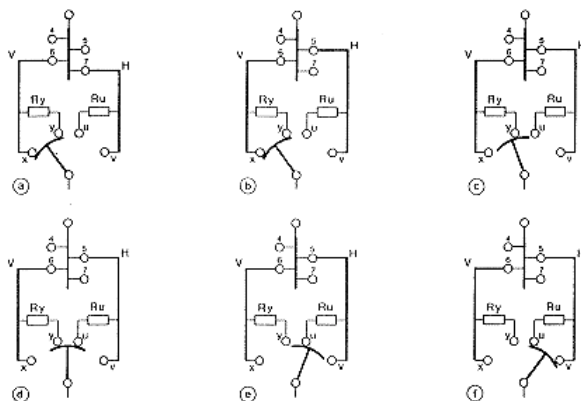
Also experimental designs of tap-changers where the changeover function is effectuated by power semi-conductor elements have been in the market. These designs also with the aim of reduced services intervals.

In resistor type tap-changers the diverter switch is enclosed in a container with oil separated from the oil in the transformer. The oil in this container will be very contaminated in due course and must be kept separate from the oil system of the transformer itself and should also have a complete separate conservator volume with its own breather.

The tap selector is a cage or an insulating cylinder with series of contacts to which taps from the regulating winding are connected. Inside the cage two contact arms move from step to step across the regulating winding. Both arms are electrically connected to the incoming terminals of diverter switch. One arm will be at actual tap position and carry the load current the other arm is unloaded and is free to move to next to come tap position. The selector contacts never break any current and can be situated in the transformer oil itself.

When the free arm has found its position the diverter switch transfer the load over. The operating cycles of the diverter is shown in Figure 7-1 Flag cycle.

Flag cycle arise from the rectangular vector diagram of transformer output voltage when moving from one tapping to an adjacent one.



Flag cycle

Figure 7-1

- The tap-changer has come from tap 7 and is presently connected at tap 6 and shall connect to tap 5.
- Selector arm H moves from tap 7 to tap 5.
- The diverter switch engages the resistor, the load current from tap 6 go through R_y .
- Step 5 and 6 are short-circuited through R_y plus R_u , the resistors are dimensioned to prevent a short circuit of the loop but also to keep acceptable voltage disturbance. The circulating current is in the range as the rated load current.
- The diverter breaks the connection with tap 6 and load current comes from tap 5 through R_u .
- Changeover resistor is bypassed and connection direct to step 5 is established.

Tap-changers for lighter duty, moderate voltages to earth and over the regulating range are of some manufacturers built in a simpler manner. In such tap-changers both the selection and switching are carried out on the same contact. The intermediate contacts and the transition resistor are mounted on one the moving arm. The arm moves in rapid jerks and passes the series of contacts that are installed along a circular arc when going from tap contact to the next. Also in this type the cycle consequently involves an interruption of power, which entails arc and contact erosion and the tap-changer housing has to be closed from the transformer oil.

Tap changers of such design is referred to as selector switch type.



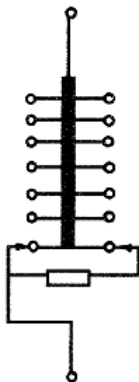
Flag cycle in a selector switch type.

Figure 7-2

Such tap-changer has also been available with a simpler transition mode, which use only one resistor. In such a single resistor type tap-changer the load current and the resistor circulating current have to be arranged to be subtractive, which dictates the power flow direction through the transformer or at least reduced rating with reverse power flow.

The single resistor type is named to follow a pennant cycle. The terms arise from the appearance of the vector diagram showing the change in output voltage of the transformer when moving from one tapping to the adjacent one.

In same manner the double resistor type is named to follow a flag cycle. The flag cycle gives no restriction to power flow direction.



Pennant cycle.

Figure 7-3

When only limited regulating range, up to 10% of nominal value, is required it is common to arrange the regulating winding for linear regulation. This means that the induced voltage in the regulating winding is added to the voltage in the main winding. For larger regulation range so-called plus-minus regulation may be more adequate. In a plus-minus regulation the tapped winding is connected to the main winding via a separate plus minus switch. This switch permits the induced voltage in the tapped winding to be added to or subtracted from the voltage in the main winding. The third arrangement is a coarse-fine regulation where the voltage regulation function is split into two winding, one for the coarse step and one for the fine steps.

Some comparisons of the three arrangements:

- All three need the same total number of turns in the windings.
- Linear need double number of steps in a fine winding compared to plus-minus or coarse-fine which is a disadvantage when larger regulation range. Both due to the design of the winding and complexity of the tap-changer.
- Plus minus need one separate winding less compared to coarse-fine.
- Coarse-fine give less load losses in the minus part of the regulation range compared to plus minus.
- The plus-minus tap-changer and the coarse-fin tap-changer are almost equal; the selector in both contains a changeover selector.

There are several different ways of arranging the regulation with regard to the size and the location of the regulation winding. A regulating winding is difficult and expensive to manufacture and it represents an insulation risk because those parts that are not connected in circuit will oscillate freely when the transformer is subjected to over voltage surges. There is every reason to make the regulating range and the regulating winding as small as possible.

In high voltage systems transformer, the windings are normally Y-connected. The location of the regulating windings can then preferably be in the vicinity of the neutral point. The insulation level to earth and between phases in the tap-changer may then be low.

Tap- changers are provided with counter that indicated the number of executed changeover operations, and of course with an indicator for the actual tapping that is connected. It is often required that this indication shall also be remotely available in the control room.

For the driving of the tap-changer there is a need for auxiliary motor power and in addition auxiliary voltages for control and monitoring circuits and indicators.

The tap-changer is a moving mechanism and actually they are the only vital parts of the transformer that do move and it should be serviced regularly.

7.3.3. Automatic voltage regulation

The tap-changer is installed to meet voltage variation in the systems connected to the transformer. It is not certain that the goal would be to maintain a constant secondary voltage at all times. The outgoing network may also have voltage drop and this may have to be compensated for as well.

The equipment for control of the tap changer does not belong to the tap-changer as such but to the relay system in the station. In principle the tap-changer just receives orders: raise or lower. However, certain functions for coordination between different transformers in the same station are part of the tap-changer technology. When different transformers are directly parallel connected their tap-changer should move in step with each other. This is arranged in such a way that one is wired as a master and the other as a slave. Absolutely simultaneous operation will not be achieved but there is a small interval with circulating current between the two transformers. This is however without any practical importance.

7.4. ACCESSORIES

7.4.1. Types of accessories

7.4.1.1. Gas actuated relay

In the connection tube between the tank and the conservator there is normally a gas-actuated relay. The relay has two functions:

- Collects free gas bubbles on their way up to conservator from the transformer tank.
- Sensitive when the oil flow between tank and conservator exceeds a pre set value.

An alternate name for this gas-actuated relay is Buchholz relay after its inventor.

Free gas may be an indication of an incipient fault within the transformer. The gas is collected in the gas relay. The gas will displace the liquid in the relay and a float will sink down. The protection is therefore arranged in such a way that when a minor amount of gas is collected in gas relay an alarm signal is actuated. If an additional amount of gas is collected tripping contact may be actuated.

When a serious fault as arcing occurs in the transformer the gas evolution will push a burst of oil up towards the conservator vessel and a flap is actuated. Sudden increase in oil flow is normally judged to be a severe indication and the signal from the flap is then wired to tripping circuit.

Relay with only one of the two functions is utilized. For instance hermetically sealed transformers without gas cushion has a small chamber on top of the cover with a float, which will actuate a contact if gas is collected. This simple relay can also be used on small transformers even if a conservator exists. A relay only sensitive to oil flow may be used between tap changer diverter switch chamber and its conservator tank.

7.4.1.2. Temperature indication

Thermometers are normally installed for measurement of top oil temperature and winding hot spot indication.

The top oil temperature can be measured directly by sensor in the oil top layer in the tank. For remote indication of top oil a Pt 100 element can be arranged as the thermometer sensor.

The measurement of winding temperature is carried out in an indirect way. The winding hot spot is assumed to be near the winding top end where it is surrounded by oil at top oil temperature. Further the temperature gradient between winding hot spot and the top oil is dependent on the losses in the winding, which in turn are proportional to the square of the current. The thermometer therefore measures the top oil temperature to which it adds the temperature difference of the winding to surrounding oil.

The winding thermometer is then arranged as a sensor inside a resistor immersed in the top oil. A current transformer, which reflects the winding current, feeds the resistor. A shunt across the resistor is adjusted to give a temperature contribution equal to the winding gradient as calculated or measured during heat run test.

For remote indication of winding hot spot a Pt 100 element can be arranged as the thermometer sensor.

Some winding thermometer designs perform the winding gradient addition in the thermometer display unit using only the top oil temperature sensor and the winding current transformer output.

The thermometers are provided with electrical contacts. At a pre set high temperature an alarm signal is given. A pre set critical temperature result in a tripping signal to the transformer circuit breakers. Additional electrical contacts may be used for control of forced cooling equipment.

Device for direct measurement of conductor temperature by fibre optics placed directly in the windings at selected spots is available.

For dry-type transformers open temperature indicators are utilized at the top area.

7.4.1.3. Built in current transformers

Current transformers can be arranged inside transformer often around the earthed sleeve of the bushing oil side, but also on low voltage bus bars. This is a matter of cost and space as well as safety. By this arrangement a number of separate current transformers in the switchyard, with both external and internal insulation for high service voltage, may be avoided.

In special cases with elevated requirements it may not be possible to provide a design around the bushing tail or on a bus bar where conceptual only one single primary turn can be realized.

7.4.1.4. Dehydrating breathers

It is necessary to exclude moisture from the air space above the conservator oil level, in order to maintain the dryness of the transformer oil. This space is vented through a device containing a drying agent usually silica gel. The property of silica gel is its high absorption power of humidity. This is total until it has absorbed water for about 15% of its weight; saturation is reached when it has absorbed 30 to 40% of its weight. Until recently the silica gel has been impregnated with cobalt chloride as colour indicator. Cobalt chloride impregnated silica gel changes from blue to pink when it is about half saturated with water. Now an environmentally friendly organic colour indicator replaces this heavy metal additive. This new type of silica gel shows an alteration from orange to colourless.

When the moisture content of the silica gel becomes excessive, indicated by the change in colour of more than 2/3 of the content, its ability to extract moisture is reduced and it is recommended that it be replaced by a further charge of dry material. Drying in an oven will reactivate the moisture-saturated gel and the colour will revert.

A refrigeration breather can be an alternative on large or important units, also when operating in very humid climates. The refrigeration breather freeze-dries the air venting into the conservator. The air in conservator over the oil will also circulate via reverse convection through the refrigeration device whether the transformer is breathing or not, so this air is continually dried in service.

7.4.1.5. Oil preservation systems

Most common is the open conservator tank where air space above the oil level is vented through a dehumidifier unit.

The transformer conservator tank can be provided with an air bag system. A synthetic rubber bag occupies the space above oil. The interior of the bag is then connected to atmosphere so it can breathe in air when transformer cools and the oil volume is reduced and breathe out when transformer heats up.

A variation is a conservator horizontally divided by a membrane or diaphragm system, which allows for expansion and contraction of the oil without actually allowing this to come into direct contact with the external air.

The space above oil in the conservator tank can be filled with nitrogen. This can be provided from a cylinder of compressed gas via a pressure-reducing valve. When transformer breathes in, the pressure-reducing valve allows more nitrogen to be released. When the volume increases, nitrogen is vented to atmosphere by means of a vent valve.

To minimize the use of nitrogen a certain span in pressure can be set between filling in and bleeding out nitrogen.

The transformers can be hermetically sealed. For smaller oil filled distribution transformers a flexible corrugated tank can take up all the expansion of oil. Other vice its necessary to provide space above oil in the transformer tank filled with either dry air or nitrogen to act as a cushion for expansion and contraction of the oil.

Some combinations have also been practiced. The transformer tank can be totally filled with oil and then equipped with an enlarged conservator tank with enough volume for oil expansion and the necessary gas cushion. The gas cushion can be extended by an extra tank, may be at ground level. To limit the volume of the gas cushion it can allow to breath to the atmosphere at set minimum and maximum internal pressures.

7.4.1.6. Oil level indicators

Oil level indicators are used to show the oil level in the conservator tank, normally as a dial instrument placed directly on the conservator tank. On large transformers the size of the dial is adapted to be readable from ground level. Oil level indicators for remote indication at the ground level are available.

The indicator may be equipped with switches for high and low oil level.

7.4.1.7. Pressure relief devices

A flash over or a short circuit occurring in oil filled transformer is usually accompanied by an overpressure in the tank due to gas being formed by the decomposition and the evaporation of the oil. The pressure relief device is aimed to limit the tank overpressure on an internal fault and thereby reduce the risk for rupture of the tank and uncontrolled spill of oil, which might also aggravate a fire associated with the fault. Low mass of the valve disc plus low spring rate of closing springs permit fast and wide opening. The valve normally closes again when the overpressure is released.

The pressure relief device is to some extent controversial. The question is whether it will operate satisfactorily. Many claim that during severe transformer faults and if the distance from the fault location inside the tank to the valve is not extremely short and direct the tank will rupture anyhow.

7.4.1.8. Sudden pressure relief devices

The sudden pressure relay is aimed to pick up the oil pressure wave in the transformer tank when a serious fault occurs. The device is able to distinguish between rapid and slow rates of pressure rise and will trip a switch if pressure increase faster than a specified rate. It permits an early detection of a fault inside the transformer and thus enables a fast tripping of the transformer. In transformer without separate conservator tank this device can substitute the sudden increase in oil flow function of a gas-actuated relay.

7.4.1.9. Over voltage protection devices

Internal over voltage protection

In some high voltage regulating winding system with large regulating range or in auto high voltage regulating transformers the designer may find it necessary to protect the regulating winding system by built in over voltage protecting elements clamping parts of the windings. Ladders of ZnO (zink-oxide) varistors elements normally arrange this.

External over voltage protection

Transformer terminals have always to be over voltage protected. The simplest way is by spark gaps on the bushings. But spark gaps as the only over voltage protection of a transformer should be limited to lower system voltages and at less important parts of the network. It is recommended to minimise the gap distance to achieve optimal protection of the transformer. Recommended arc horn gap distance depending of transformer BIL is set in following table.

System voltage kV	BIL kV	Distance mm
12	75	60
17.5	95	70
24	125	100
36	170	140

The intention of using only spark gaps overvoltage protection of a transformer should be stated in the technical specification.

Better protection is achieved by surge arrestors located close to the terminals as possible, direct on the transformer tank or adjacent to the transformer. Also the ground connection between the arrestor pad and the transformer tank should be as short and direct as possible.

If over voltage protection has to be situated some distance apart from transformer due to for instance direct connection to SF6 switchgear or direct cable connection this has to be taken into consideration when selecting transformer insulation level.

See also section 15.2 page 167.

7.4.1.10. Transport wheels/skids

It is normally not practical to lift larger units by crane direct to final position on fundament, it have in some way to be moved from the vehicle to the pad. If a cast-in rails system exist between unload area and final position the unit may be equipped with wheels allowing it to be rolled in. 90 degrees turn in transport direction can be arranged by bi-directional wheels. The unit is jacked up and the wheels are turned. In position the unit can be left on its locked wheels or the wheels can be removed and replaced by support blocks or the unit can be lowered down directly on the fundament.

If no rail system exists a temporary system of normally flat beams is arranged and the unit is pulled directly in position on greased beams or by help of caterpillar tracks.

When in position the unit may be welded to the foundation. It may also be placed on vibration pads to reduce the sound transmission to the foundation.

How to transport and position the unit onto the foundation has to be clarified at an early stage between the purchaser and the manufacturer. Also to be clarified are that transport beams, jacking points, both at the transformer and at the foundation, as well as hauling hooks have correct dimensions and are in the best position.

7.4.1.11. Combustible Gas Detector

The combustible gas detector indicates hydrogen in the oil. The hydrogen is picked up through a dialytic membrane. This system gives an early indication of slow gas generation before free gas in oil starts bubbling towards the gas accumulation relay. It may be used in addition to a gas-actuated relay because it gives earlier warning. In transformers without separate conservator tanks this detector substitute the gas accumulation function of a gas actuated relay.

7.4.1.12. Flow indicator

For the control of the oil flow out of the pumps on transformer with forced oil cooling equipment, oil flow indicators are installed. The indicator is often based on a method of measuring the pressure difference across an obstacle in the oil flow.

Flow indicators are also used in the water flow of water-cooled transformers.

The indicators are normally equipped with an alarm switch. It can also include a dial.

7.4.2. Power transformer and oil immersed reactor accessories

Minimum accessories:

Gas actuated relay with alarm and trip

Top oil thermometer with alarm and trip

Oil level indicator with alarm at high and low level

If OLTC:

Tap-changer protection device with trip

If oil forced cooling:

Oil flow indicator with alarm

Optional:

Winding hot-spot thermometer with alarm and trip

7.4.2.1. *On line monitor systems*

Within ABB, different on line monitoring systems for different purposes are available.

There is one system for recording of transient voltages, e.g. caused by operations of circuit breakers. By using this system, dangerous situations caused by overvoltages can be revealed. The system gives information about different kinds of overvoltages and corrective measures can be taken.

Other systems available are surveillance systems that continuously record some key parameters via sensors. These parameters are all essential to determine the condition of the transformer and to identify possible faults. Such systems work with models, which get their input values from the sensors. The models are advanced calculation algorithms based on standards, design and ABB knowledge that compare the output with preset limits. As mentioned the input values to the models come from the sensors. The most essential parameters measured are:

- Key gases in oil
- Water content in oil
- Temperatures
- Load currents
- Line voltages
- Partial discharges (PD)
- Dissipation power factor in bushings

The models available are as follows:

- Continuous calculation of load
- Winding hot-spot calculation
- Insulation ageing, consumed lifetime
- On load tap-changer contact wear and tap position tracking
- Moisture analysis, moisture in oil/paper, bubbling temperature
- Cooling efficiency
- Cooling control

In addition manual models for calculation gas analysis based on user input are available.

7.4.3. Distribution transformer accessories

This is a list of available accessories to be selected in cooperation with the user.

Accessory type	Type of transformer		
	SDT/MDT	LDT	Dry
Tap changer			
Off-circuit	S	O	Bolted links On request
On-load	O	O	
• Voltage regulation relay		O	
• Electrical position indicator		O	
• Parallel operation equipment		O	
Conservator	O	S	NA
Silicagel dehydrating breather	O ¹⁾	S	NA
Pocket, top liquid thermometer	O ²⁾	S	NA
Dial thermometer	O	S	S
Pressure relief valve	S ⁴⁾	O	NA
Pressure relief device with signal	O	O	NA
Gas-actuated relay	O	S	NA
Integrated protective device mounted on the cover	O	O	NA
Temperature monitoring system	NA	NA	O
Earthing terminals	S	S	S
Wheels, (bi-directional)	S ²⁾	S	S
Drain valve at tank bottom	S	S	NA
Liquid level gauge	O ³⁾	S	NA
Liquid sampling valve	O ³⁾	S	NA
Cable boxes on LV – and HV side mounted on the cover	O ⁵⁾	O ⁵⁾	NA
Plug in HV & LV bushings equipped with the robust protections	O	O	NA
Enclosures (of different protection class)	NA	NA	O
Overvoltage protection devices			
• Surge arrestors	O	O	O
• Arching horns	O	O	NA
Overcurrent protection, fuses	O		
Built-in current transformers	O	O	O
Multi function devices; pressure, temperature, oil level and gas	O	O	NA

The abbreviations S (standard accessory), O (optional) and NA (not applicable) are an indication of where the different accessories are most common in use.

¹⁾ Only used when conservator

²⁾ Thermometer pocket is an option on SDT and standard on MDT.

³⁾ Standard on SDT/MDT with conservator

⁴⁾ Standard on hermetically sealed

⁵⁾ Plug-in bushings is the preferred ABB solution instead of cable boxes due to easy assembly and lower cost and reduced distances in the substation

8. INSTALLATION AND COMMISSIONING

This section describes ABB's general experience/recommendations and minimum requirements, however it may be overruled or supplemented by local regulations and the supplier's or purchaser's specific instructions.

8.1. GENERAL

8.1.1. Responsibilities

For power transformers, the installation and commissioning are normally performed by ABB. Distribution transformers are normally installed and commissioned by the buyer.

In some cases the installation and commissioning is e.g. performed by the customer and supervised by ABB.

Responsibilities are defined in the purchase contract with reference to General conditions, e.g. ORGALIME.

Limitation of responsibilities should be defined, e.g. when recommended protection is not installed.

8.1.2. Incoterms (Transfer of responsibility)

Incoterms defined by International Chamber of Commerce (ICC) make international trade easier and help traders in different countries to understand one another.

Incoterms are standard definitions of trade terms and are internationally recognized as indispensable evidence of the buyer's and seller's responsibilities under a sales contract. Incoterms will not apply unless specifically incorporated into the contract

Those standard trade definitions that are most commonly used in international contracts are protected by ICC copyright, however a wall chart may be viewed on http://www.iccwbo.org/index_incoterms.asp where a wall chart in preferred language may also be purchased.

8.2. INSTALLATION

8.2.1. Power- and large distribution transformers

Installation and commissioning should preferably be performed by the supplier or in close cooperation with the supplier. The contract describes what to be performed by the parties.

8.2.1.1. *Allocation of responsibilities between supplier and purchaser*

After the Factory Acceptance Test (FAT), the transformer is disassembled and made ready for shipping. Depending on the size and voltage class of the transformer more or less of the equipment on the transformer is dismantled prior to transport. Normally conservator, coolers and high voltage bushings are dismantled prior to shipping and transported separately. Usually large power transformers are shipped without oil. When the transformer is shipped without oil, the transformer oil is transported on tank lorry suited for this purpose and/or in barrels. During transport the transformer is filled with dry air with a certain overpressure in order to avoid moisture absorption in the insulation. Before leaving the factory a tightness test is performed. Smaller transformers like large distribution transformer might be shipped with oil. The weight limit for when the transformer is transported with or without oil depends on several factors like the transport facilities (trucks, boat, cranes), weight limits on roads, bridges etc.

For transformers with a transport weight above 20 ton, which usually is the case for power- and large distribution transformers, special transport is required. This means, transport is performed by experts in handling heavy goods.

During transport, the transformer should be equipped with an impact recorder. This is to record if anything should happen to the transformer during transport and during handling at site. Some recorders register impacts (G-forces in x, y and z-direction) and exactly when the impacts occur. This is essential in the event the transformer has been exposed to abnormal impacts and to determine which party has the transport responsibility at the time of the impact. The recorder shall not be dismantled and the recording finally read before the transformer is at its final destination. If specified, this shall be performed in the presence of the parties responsible for the various sections of the transport.

The transformer should be insured during the transportation either by the supplier or the purchaser, depending on the terms of delivery (INCOTERMS, see section 8.1.2 page 110). Terms of delivery are included in the contract between the supplier and the purchaser.

E.g., if the terms are EXW, the purchaser takes over the responsibility (risk) for the transformer when it is leaving the supplier's premises. If this is the condition, it is up to the purchaser whether or not the transformer should be equipped with an impact recorder.

When ABB supplies new power- and large distribution transformers, the preferred terms of delivery normally are DDP or DDU. In this case the supplier (ABB) is responsible for the transformer until the arrival at the agreed destination. The transformer should then be equipped with impact recorder.

When the transformer arrives at site, it shall be inspected. During this inspection all necessary documentation shall be available. Representatives from the supplier (supervisor) should be present during this inspection. In any case, in the event of possible transformer damage during transport, the supplier shall be notified and consulted before any actions are taken. If the purchaser unloads a transformer with possible transport damage without consulting the supplier, the purchaser has the full responsibility.

If it is specified that all handling, lifting, installation, oil filling and oil processing shall be carried out by the supplier or under supervision of a representative from the supplier the warranty is only valid when this requirement is fulfilled. The impact recorder shall not be removed until the transformer is placed and fixed on its final site foundation.

If storage of the transformer is required prior to energising this shall be performed according to the supplier's instructions and the conditions for extended warranty shall be agreed between the parties.

8.2.2. Distribution transformers

8.2.2.1. Transport

The transformer is supplied filled with liquid and normally all accessories fitted, except for the largest units. The radiators may be dismantled during transport.

During transport the following should be considered:

- Angle of tilting exceeding 10° must be specified in the contract,
- Prevention of damage to bushings, corrugated panels or radiators and accessories,
- Larger transformers should preferably be positioned with the longitudinal axis in the direction of movement,
- Secure against movement by means of e.g. wooden blocks and lashes,
- Adapt vehicle speed to the road conditions,
- Vehicle capacity shall be adequate for the transport weight of the transformer,
- Any impact recorders to be specified in the contract,
- Any use of crates or containers.

8.2.2.2. Handling, lifting

Only approved and suitable lifting equipment shall be used.

Use a forklift only on transport pallets or transformer bottom.

Do not apply load to corrugated fins or radiators and their supports.

Use the provided lifting lugs only.

When lifting a transformer with cable boxes on the cover, special care must be taken.

When hydraulic jacks are used, only provided jacking points shall be used, and in such a way that twisting forces on the transformer tank are avoided.



Transformer lifting example

8.2.2.3. *Receiving the transformer at site*

Transformers manufactured by ABB are thoroughly tested and inspected prior to shipping, but upon receiving the transformer at site, it should be inspected carefully.

To be inspected:

- The way in which the transformer has been secured on the trailer,
- That the delivery is complete according to order confirmation,
- Compare the packing list with the goods received,
- The transformer nameplate,
- Liquid level, when applicable. Any leakages?
- External damage, e.g. cracks in bushings,
- Impact recorder indications when applicable.

The receipt of the unit shall be signed for and the result of the inspection shall be noted.

Transformer shipments are normally insured.

In case of damage revealed during the receiving inspection do any of the following:

- Make necessary arrangement to avoid further damage,
- Contact the insurance company concerned and ABB,
- Make a report of the damage immediately,
- No repairs should be started until responsibilities are clarified and actions are agreed upon all involved parties.

8.2.2.4. *Storage prior to energizing*

When storage of the transformer is required, the following recommendations should be noted:

- Preferably in dry and clean locations, without any possibilities of mechanical damage and on a solid foundation,
- If the transformer does not have a structural steel base, it should be placed upon supports to allow ventilation under the bottom of the transformer base,
- The liquid conservator and dehydrating breather must be checked to ensure that dry air is breathed. (Conservator type only) Liquid samples to be analysed regarding moisture content prior to energizing,
- Humidity/condensation in control cubicles, driving mechanism for on-load tap changer, cable boxes, dry-type transformers etc. should be inspected/removed,
- Minimum storage temperature for dry-type transformer is in general -25°C, however for Resibloc -60°C,
- Prior to energizing, perform a megger test between the different windings, and from the windings to earth. This applies to dry-type in particular.

8.2.2.5. Erection at site

In determining the location of a transformer, give careful consideration to accessibility, safety, ventilation and ease of inspection. Make sure the foundation for mounting the transformer is entirely adequate.

Ventilate the erection site properly. As a guide each kilowatt of losses requires 4 cubic meters of air circulation per minute. Fresh air intake at floor level, and a ventilation duct leading to outer air must be built into the ceiling or upper part of the wall. The intake and outlet openings should be located at opposite sides of the room. The duct cross section of the outlet should be 10 % more than the cross section of the inlet opening due to the increase of volume of the hot air.

Observe local authorities regulations for civil engineering of transformer cells, safety regulations, fire protection regulations. A liquid containment tank may be required.

A transformer equipped with wheels must be prevented from moving by chocking the wheels.

8.2.2.6. Network connection

8.2.2.6.1. Electrical clearances in air

Maximum system voltage (kV)	3.6	7.2	12	17.5	24	36	72.5
Lightning impulse withstand voltage (kV)	45	60	75	95	125	170	325
Minimum clearance according to IEC 60076-3, phase to phase and phase to earth. (mm)	60	90	110	170	210	280	630

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Note: Testing or well documented local practice can allow the use of reduced clearances.

8.2.2.6.2. Connecting transformer terminals to the networks

Observe local authorities safety regulations and regulations for electrical installations.

Conductors, bus bars and cables shall be installed such that minimal mechanical stress is transferred to the bushings.

Conical washers shall be used in order to obtain the required contact pressure. Nuts should be adequately locked.

Flexible connectors shall be used between the terminals and the bars, when connecting to low voltage busbars. Suitable cable lugs shall be used when connecting low voltage copper cables.

High voltage connection is normally performed by copper cables and copper cable lugs. In some cases heat shrinkable connectors or elbow connectors are used.

For aluminium-copper joints the copper is coated with tin, or bi-metal sheets (one side of copper and the other of aluminium) can be used between the joint.

The aluminium surface must be larger than the copper surface.

Aluminium parts shall always be placed above copper parts so that water cannot drain from the copper parts onto the aluminium (corrosion).

It must be remembered that good contact between joined aluminium surfaces can be achieved only if the no conducting oxide film is removed with a wire brush, file or similar immediately before joining, and renewed oxidation is prevented by applying a thin protective film of grease (petroleum jelly).

Jointing compound, which prevents the access of air and humidity into joints, must be used in the joint. The zinc crystals of the compound break down the layer of oxide on the aluminium.

Minimum electrical clearances shall be obtained.

Suitably strong steel bolts and nuts must be used for tightening the joint. The tightening torque values given below are recommended to be used in external transformer joints.

Cable and busbar load capacities are outside the scope of this handbook, however dealt with in detail in ABB Switchgear Manual.

8.2.2.6.3. Tightening torque

Bolt size	Recommended tightening torque/Nm	
	Property Class	
	Bolt 8.8	Nut 8
M5		3,0
M6		5,5
M8		15,0
M10		30,0
M12		60,0
M16		120,0

When disk-type spring washers are used, the nuts should only be tightened until the washer becomes flat.

8.2.2.7. Earthing

Earth the transformer at the earthing terminals provided.

Earthing resistance according to electricity utilities- or national standards

8.2.2.8. Protective equipment

Connect the equipment, and check the functions:

- Thermometer with contacts for alarm and tripping signals,
- When applicable, oil level indicator with contacts for alarm signal,
- Gas relay with contacts for alarm and tripping signals,
- Pressure relief device with contacts for alarm signal. When provided,
- Recommended thermometer settings for ONAN transformers.

Type of temperature equipment	Alarm	Tripping
Oil thermometer setting	85°C	100°C
Oil thermometer setting, when combined with a winding temperature indicator	90°C	105°C
Winding temperature indicator setting	105°C	135°C

- Recommended thermometer settings for dry-type transformers according to the relevant temperature class.

Temperature class	Alarm	Tripping
105 (A)	90°C	105°C
120 (E)	105°C	120°C
130 (B)	115°C	130°C
155 (F)	140°C	155°C
180 (H)	165°C	180°C
200		
220		

8.2.2.9. Insulation resistance

Check the insulation resistance between HV and LV as well as windings to earth. Minimum value is 1000 ohm per volt service voltage (Maximum 1mAmp.),

8.2.2.10. Off-circuit/on-load tap changer

- Check the galvanic contact between the winding and the tap-changer in all positions,
- Compare the voltage ratio of the transformer and the network voltages, and select the suitable tap changer position.

8.2.2.11. Mechanical checks

- Check the liquid level,
- Tighten all leaking gaskets carefully,
- After completed installation work, surface damage caused by transportation and installation work shall be repaired,
- Condition of dehydrating breather. (For conservator type only),
- Finally the transformer must be cleaned.

8.3. COMMISSIONING

8.3.1. Energising

Prior to energising, the transformer has to be checked. If applicable the following items should be reviewed:

- Inspection of transformer
- Check impact recorder:
 - If impacts above a certain level are recorded the transformer must be checked for transport damage,
- Check, painting, leakages and fastening:
 - Conservator, cover, tank and coolers
- Bleeding:
 - Cover, bushings, tap changer, Buchholz relay, cooling equipment
- Earthing of:
 - Transformer, cabinets, current transformers, surge arresters, RC-network, tap-changers, oil filter etc.
- Cooling equipment:
 - OFWF: Check the mounting direction of oil pumps, oil flow-, and water flow indicators. Adjust water- and oil flow indicators. Check the rotation direction of the motors, motor voltage, motor protection. Check that all valves are open
 - OFAF: Check the mounting direction of oil pumps, oil flow indicators. Adjust oil flow indicators. Check the rotation direction of the motors, motor voltage, motor protection. Check that valves are open.
 - ONAF: Check the rotation direction of the motors, motor voltage, motor protection, check that valves are open
 - ONAN: Check that valves are open
- Tap-changer, oil filter and motor drive unit:
 - Should be checked according to guidelines given by the manufacturer for this equipment, e.g. locking of shaft connections, mounting direction protective relay, symmetrical coupling, motor voltage, phase rotation, motor protection, end limit switches (electrical and mechanical), emergency stop – raise and lower switch, step by step, remote controlling etc. The checklist may vary depending on selected manufacturer, type of tap-changer and equipment installed.
- Current transformers:
 - Check polarity, and that all secondary CT circuits are closed before energising the transformer. If a current transformer is not in use it has to be short circuited and earthed. An open circuited current transformer gives hazardous voltages and is dangerous to personnel and equipment. It can result in personal injury, death or property damage.
- Protective equipment:
 - Check that all alarm signals from protective equipment is functioning, such as thermometers, oil level indicators, Buchholz relay, oil flow-, water flow indicators etc.
 - Check that all trip signals from protective equipment is functioning, such as thermometers, oil level indicators, Buchholz relay, tap-changer protective relay, etc. Trip signals are hard wired to the circuit breaker and all trip signals should be checked to verify that the circuit breaker opens when a trip signal is activated.

- Oil sample:
 - Oil sample must be collected and analysed to check that the oil condition (dielectric withstand voltage and moisture level) fulfils the requirements of IEC or ANSI/IEEE standards.
- Electrical tests:
 - Electrical tests recommended by the supplier should be performed.

After the transformer has been found to be in good condition and the protective equipment is found in order according to the above list, the transformer is ready to be connected to the network (energised).

In particular, when connecting distribution transformers to the network, fuses may blow immediately caused by high inrush current. This does not necessarily mean that there is a fault in the transformer. Replace blown fuses and try energising again because the magnitude of the inrush current is a statistical variable with large spread. Modern over-current and differential relays contain a filter which makes the relays insensitive to inrush currents. Older relays may trip the circuit breaker immediately. See also section 11.7 page 141, paragraph "Inrush current". After the transformer has been connected to the network, gas may be present which cause the gas relay to trip to give an alarm. It could be a false alarm caused by an air bubble, trapped under the cover, and then moved into the gas relay. Air is colourless and odourless. If not air, a gas and an oil sample should be taken for analysis.

Date for formal take-over can vary, but shall be clearly stated in the contract between supplier and purchaser. This can be after the transformer is energised or after a test period of the transformer. A hand-over protocol should be established, signed by both parties, see also section 8.1.2 page 110.

8.3.2. Documentation

The following documentation will be handed over to the purchaser at time of take-over as applicable:

- Transformer specification
- Outline drawing
- Transport drawing
- Schematic drawing
- Wiring diagram
- Assembly, operation and maintenance manual
- Technical documentation from sub suppliers (bushings, tap-changer, coolers etc)
- Data sheet transformer oil
- Test protocol (FAT)
- Transport (shipping) documentation
- Trouble shooting guide
- Commissioning report.
- Take-over protocol

9. OPERATION, MONITORING AND MAINTENANCE

9.1. GENERAL PRECAUTIONS

- Perform a safety job analysis before the work starts,
- Never work on transformers or any installed electrical equipment alone,
- Do not change the position of off-circuit tap-changers while the transformer is energized,
- Do not energize or perform maintenance on the transformer without proper earth connection,

For more information see section 3.3 page 60 on safety aspects.

9.2. OPERATION

9.2.1. Lifetime

The lifetime of a transformer can be divided into two categories; economical and technical.

Economical lifetime:

Economical lifetime ends when the capitalized cost of continued operation of the existing transformer exceeds the capitalized cost of a new investment.

In practical terms; typically when the cost of the total losses of the old transformer are too high.

Consequential risks and costs associated with electricity downtime are of increasing importance.

Technical lifetime - The ageing process of cellulose:

The cellulose materials undergo chemical degradation – ageing – in service. The dominant processes have the character of oxidation and result in breaks of the long cellulose chain molecules into shorter fragments, and the material becomes gradually more brittle. Old paper breaks up into small flakes. But even in this state the dielectric breakdown voltage is hardly affected at all.

The practical consequence of the ageing is a higher risk of mechanical rupture and metal-to-metal contact as a result of mechanical shock and vibrations.

The cellulose molecule has a ring structure as shown to the left in Figure 9-1. Several of these molecules are linked together to a chain by oxygen atoms. This is called polymerisation.

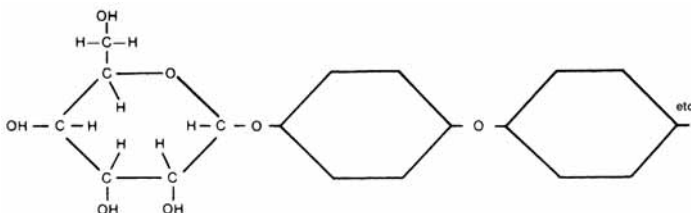


Figure 9-1

There is a standardised method of chemical analysis which provides information of the average number of rings in the chains of cellulose molecules. This number is called the degree of polymerisation, or abbreviated, the DP number. Virgin paper made of slow growing pine in cold climate has typically a DP number of 1200 – 1400. There is a correlation between the DP number and the tensile strength of the material and the degree of ageing can be expressed by the decrease in DP number. When the DP number has fallen to 200, the material is quite brittle. It is common to express the condition of the material by means of the DP number instead of the tensile strength because the DP number can be determined with less measurement uncertainty than the tensile strength when the ageing process has come to a certain stage.

The ageing is a cumulative process depending on influences from the environment in the transformer. The rate of the chemical reaction rises with the temperature. V. M. Montsinger's rule, established after many years of intensive research, states that the rate of the chemical deterioration process is doubled for each 6-7 °C temperature rise. However, this rate is considerably increased by the presence of water molecules and free oxygen dissolved in the oil.

As the paper due to ageing becomes gradually weaker in respect of tensile strength there will be a correspondingly increasing risk that the transformer will fail if a short circuit in the power system occur. In absence of such external events the transformer may operate satisfactorily even with solid insulation with very low DP numbers because the compressive strength and the dielectric strength of the cellulose are hardly reduced at all by the ageing process.

Short circuit tests that demonstrate the ability of a transformer to withstand the short circuit currents are almost always performed on new transformers which never have been in service. The so-called 'end of life' term is a matter of definition. The term could be related to a percentage of the original tensile strength of the insulation, for example 50, 25 or 10 %, or to an absolute value of the tensile strength in N/mm². Or to a certain minimum of the DP number. There is no universally valid figure to choose. The likelihood of short circuits in the power system plays an important role.

A comprehensive international investigation performed some years ago concluded that the failure rate of large power transformers due to short circuit currents was very low, 3 failures per 25 000 transformer service years, that is 0,12 per thousand. The investigation included both 'young' transformers and transformers that have been in operation for several decades. This failure rate might increase sometime in the future due to further aging of the whole bulk of transformers in service. In general, for the time being the rate of failures due to short circuit currents does not seem to be a matter of large concern. However, it is justified to make efforts to keep the interior of the transformer dry and clean.

Cellulose is one of the most hygroscopic existing materials, which means that it has a high ability to absorb moisture. When stored in air, the water content is typically 5 – 10 % by weight, dependent on the relative moisture content in the ambient air. Cellulose with that high moisture content would be unsuitable for insulation in transformers because moisture from the cellulose would be transferred to the oil and would drastically reduce the dielectric strength of the oil. In addition the ageing process in the cellulose would be accelerated.

To make the cellulose a suitable insulation material it has to be dried to moisture content well below 1 % before filling the oil on the transformer in the factory. The high temperature needed in this drying process will cause a noticeable reduction in the original DP number of the cellulose.

In order to keep the tensile strength of the cellulose materials as good as possible in service, penetration of moisture from the ambient air into the transformer can be avoided by making the tank hermetically sealed on smaller distribution transformers. For larger transformers it is recommended to separate the oil in the conservator from the air by means of a diaphragm.

However, water and free oxygen will be produced inside the transformer due to the natural ageing process. The water content in the oil can be measured from oil samples taken from the transformer. From the water content in the oil the water content in the cellulose insulation can be estimated by means of the diagram in Figure 9-2.

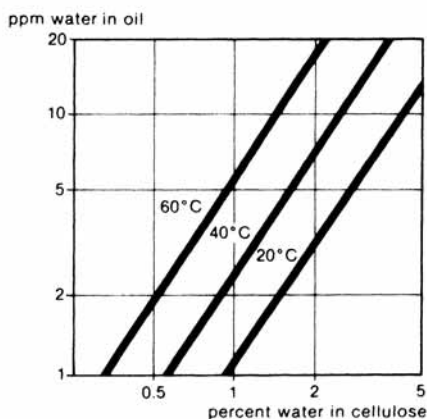


Figure 9-2

The diagram shows equilibrium lines for the water content in cellulose and the water content in oil. The equilibrium condition depends on the mean temperature of the oil. 10 ppm water in the oil corresponds to 1,5 % water in the cellulose at 60 °C oil temperature. At 20 °C 10 ppm in the oil corresponds to 4 % in the cellulose. So, in order to estimate the water content in the cellulose from the water content in an oil sample, it is important to know the average oil temperature when the oil sample was taken.

The cellulose is able to absorb much more water than the oil although the quantity of oil is much larger than the quantity of cellulose. The cellulose is the large reservoir of water in the transformer, not the oil.

From the diagram it appears that if the cellulose contains for example 2 % water and the temperature increases from 20 to 60 °C, the water content in oil increases from 3 to 18 ppm. In other words, by increasing the temperature water is transferred from the cellulose to the oil. However, while the increase in the water content in the oil is considerable, the relative decrease in the water content in the cellulose is very small. From this consideration the conclusion is that drying the oil is not an efficient method to remove moisture from the cellulose.

If the water content in oil samples indicates that the water content in the cellulose after some years in service has increased beyond an acceptable value, the oil must be emptied from in the transformer before any drying process to remove the water from the cellulose starts.

The diagram in Figure 9-3 shows how the ac breakdown field typically declines with increasing moisture content at 20 °C temperature. (Tested according to IEC 60156 (1995-08) Insulating liquids – Determination of the breakdown voltage at power frequency – Test method).

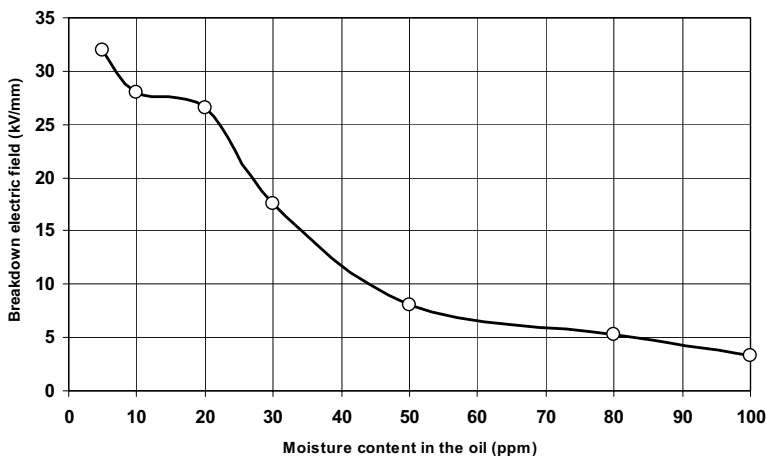


Figure 9-3

The moisture content in the oil when performing the delivery test on a new transformer is maximum 5 ppm. It should be noted that the ac breakdown field declines quite much as soon as the moisture content exceeds 20 ppm. Consequently there will be a fall also in the dielectric strength and the service reliability of the transformer.

Figure 9-4 shows how the DP number decreases with the time in a test at 120 °C. In a new transformer the moisture content in the solid insulation is dried to 0,5%. The curve in Figure 9-4 is the result of a material test where samples with 3% and samples with 0,5% moisture content at the beginning of the test were exposed to 120 °C. The vertical axis indicates the quotient of simultaneous values of DP numbers. The declining curve that the DP number for the samples with 3% moisture is reduced at a higher rate than the samples with 0,5% moisture [5].

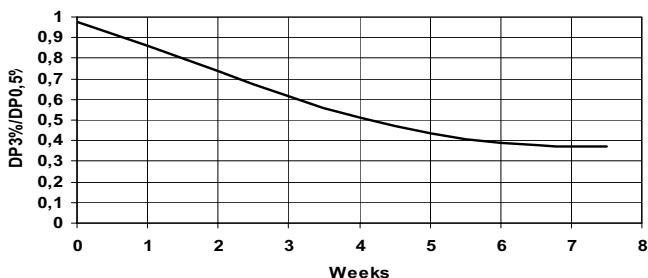


Figure 9-4

Keeping the moisture content in the solid insulation and in the oil low increases the probability of reliable transformer operation during many years, often more than half a century.

IEC 60076-7 Ed. 1: Loading guide for oil-immersed power transformer provides simplified methods on how a theoretical consumption of insulation life can be calculated when overloading transformers continuously and temporarily.

Practical experience shows that many transformers have been operated satisfactorily until a change in system voltage has necessitated a replacement.

9.2.2. Temperature rise and load capacity

Thermal class 105 is defined to withstand a continuous temperature of 105 °C for 7 years, without losing more than 50 % of its original mechanical strength. Class 130 is defined to withstand a continuous temperature of 130 °C for 7 years, and so forth for all other insulation classes.

The sum of ambient + average temperature rise of any of the windings + 10° C (to allow for that maximum temperature rise in a winding is 10 °C above average) should not exceed 105 °C.

Ageing sets certain limitations to the load capacity of the transformer. These limitations are defined in IEC publication 60354 "Loading guide for oil immersed transformers". (Within short time to be replaced by IEC 60076-7).

Continuous load capacity at different constant ambient air temperatures has been calculated according to IEC 60354.

Permissible continuous symmetrical loading capacity at different ambient air temperatures for ONAN distribution transformers.

Constant ambient air temperature °C	0	+10	+20	+30	+40	+50	+60
Permissible continuous load factor, % Temperature rise 60/65 °C	116	108	100	91	82	72	-
Permissible continuous load factor, % Temperature rise 50/55 °C	-	119	110	100	89	77	64

In practice the transformer is not continuously fully loaded. The load and the temperature fluctuate by seasons and time of the day.

The permissible short-term overload depends on the starting conditions, plus duration and the repetitive cycle of the overload. This is defined in the IEC 60354, and must be analysed on a case-to-case basis.

Based on the above there is a certain emergency overload capacity for the transformer.

Special attention shall be paid to the fact that the transformer's short term load capacity cannot be judged on the basis of the oil temperature alone, because the oil temperature changes much slower with the load than the temperature rise of the winding.

Overloading a transformer implies that the construction and the accessories, such as the tap changer and the bushings are correspondingly rated. Normally the accessories are selected with rated current not less than 120% of rated current of the transformer. (For bushings see IEC 60137).

Corresponding considerations are made for dry-type transformers, and are described in IEC 60905 Loading guide for dry-type power transformers (Under updating).

From IEEE STD C57.91-1995 8.1.2 Normal life expectancy

The basic loading of a distribution transformer for normal life expectancy is continuous loading at rated output when operated under usual service conditions as indicated in 4.1 of IEEE Std C57.12.00-1993. It is assumed that operation under these conditions is equivalent to operation in a constant 30 °C ambient temperature. The hottest-spot conductor temperature is the principal factor in determining life due to loading. Direct temperature measurement of the hottest spot may not be practical on commercial designs. The indicated hottest-spot temperatures have therefore been obtained from tests made in the laboratory and mathematical models. The hottest-spot temperature at rated load is the sum of the average winding temperature and a hottest-spot allowance, usually 15 °C. Normal life expectancy will result from operating continuously with hottest-spot conductor temperature of 110 °C or an equivalent daily transient cycle. For mineral oil-immersed transformers operating continuously under the foregoing conditions this temperature has been limited to a maximum of 110 °C. Normal life expectancy of transformer insulation using different criteria is given in table 1 in IEEE STD C57.91-1995. Distribution and power transformer model tests indicate that the normal life expectancy at a continuous hottest-spot temperature of 110 °C is 20,55 years.

9.2.3. Parallel operation

When two or more transformers are connected in parallel the following is required:

- Only transformers having the same phase displacement between primary and secondary voltage can operate in parallel. The clock-hour which indicate the phase displacement is stamped on the transformer rating plate, e.g. Dyn11, Yd11,
- Poles with the same polarity on HV- and LV side shall be connected in parallel,
- Transformers should have approximately the same voltage ratio,
- The short-circuit impedance voltage should be the same, within $\pm 10\%$,
- The power rating of the transformers should not deviate more than 1:3,
- Tap changers should have tap position giving voltage ratios as close as possible.

Deviation from the above requirements is possible, provided adequate knowledge is available.

For further details, reference is made to IEC 60076-8 (Power transformers – Application guide clause 6 page 81- 91).

9.2.4. Frequency

A transformer designed for 50 Hz can be used for 60 Hz but not vice versa, however electric equipment for accessories should be considered.

9.2.5. Protection

9.2.5.1. Overcurrent protection

There are two types of overcurrent protection:

- Fuses,
- Overcurrent relays which send tripping signals to the circuit breaker.

Overcurrent protection is mainly intended for protection against high overcurrents due to external short-circuits.

9.2.5.2. Differential protection

Differential relays react upon different ampere-turns on the two sides of the transformer which indicates that there may be an internal fault in the transformer.

9.2.5.3. *Alarm and trip signals from the transformer*

Signals from the transformer can either be local or remote. The accessories on the transformer determine the kind of signals. This is again depends on the type of transformer and customer requirements.

In its simplest form the signal is local and with only visual indication at the transformer, which e.g. may be from a liquid level indicator or a dial thermometer measuring the top oil temperature.

From most accessories remote signals may be collected. The normal way to do this is to transfer all signals to a common connection box on small transformers, or to a termination cabinet for larger transformers. From here the customer may transfer the signals further to a control room.

Examples:

- Top oil temperature
- Winding temperature
- Gas actuated relay
- Oil level indicator
- Pressure relief devices
- Oil and water flow indicators
- On-load tap-changer position indication
- On line monitoring system

See section 7.4 page 104 for further details on accessories.

9.2.5.4. *Over voltage protection*

See section 15 page 164.

9.3. **MONITORING**

9.3.1. **General**

Most transformers are equipped with protection systems to avoid damage to the transformers, the network or both, in the event of non-normal operation of the transformer or the network. Examples of such protection systems are the network and transformer protection current transformers mounted usually at the transformer terminals feeding relays (overcurrent, differential), the gas and oil activated relay (Buchholz) and the winding and oil temperature indicators (WTI and OTI). These systems are common to most power transformers, including some distribution transformers. However, monitors are mostly confined to medium to large power transformers, in particular those that are strategically important in a network or, as in the case of generator step-up transformers and HVDC converter transformers, where the transformers are the only means of power transfer in networks. An unplanned transformer outage in these networks can have severe technical and economic consequences for the network operator. The main purpose of fitting monitors to these transformers is for condition assessment with the purpose of mitigating some of the above difficulties [Draft IEC 61378-3 Converter transformers - Part 3: Application guide].

Monitoring of transformers can roughly be divided in high and low level monitoring.

- High level
 - On-line monitoring
- Low level
 - Periodic recording of a few parameters, visual inspection
 - Oil condition monitoring
 - Off-line monitoring

9.3.2. High level monitoring

The major goals of an on-line monitoring system are to prevent major failures, to achieve better utilisation of load capacity, optimise maintenance and to extend the remaining lifetime. Transformers of strategically importance should be equipped with on-line monitoring systems in order to ensure reliable operation, a minimum of maintenance (condition based maintenance) and low life cycle cost.

The on-line monitoring system receive and archive all information needed from just a few sensors, other necessary parameters are calculated based on the compiled data. The on-line monitoring system receives typically the following information from sensors:

- Temperatures
- Gas in oil
- Moisture
- Partial discharge
- Currents
- Voltages
- Tap Changer

The measured and calculated parameters are used in algorithms used in models for calculating and recording:

- Cooling/overload forecast
- Real-time status/availability
- Lifetime
- Event recording
- Condition based maintenance
- Operation and updates

E.g., by knowing the current at each OLTC operation and the number of operations, the wear of the contacts can be calculated. Maintenance can then be performed as condition based instead of periodically. The advantage of condition based maintenance, is that the maintenance is performed when necessary and not too early or long overdue. With such systems, early warnings are given and necessary precautions with regards to maintenance can be taken in order to avoid failures that may have large economical consequences.

Systems for control and monitoring are available within ABB. One of the systems is TEC, which is a transformer control and monitoring system that new transformers can be equipped with. Figure 9-5 shows the layout of the TEC system.



Figure 9-5

Older transformer can be equipped with a monitoring system called T-Monitor.

9.3.3. Low level monitoring

Most transformers have a minimum of monitoring. Low level monitoring can be divided into the following:

- Periodic recording of a few parameters, visual inspection
- Oil condition monitoring
- Off-line monitoring

Periodically recording is normally done when the transformer is energised. It is important to take the necessary safety precautions when the inspection is performed. The parameters recorded can be oil level, top oil temperature, winding temperature, load current and the number of operations since last maintenance of the tap-changer. The amount of equipment will vary depending type of transformer, importance of transformer, etc. Depending on the importance of the transformer the recording of these parameters could be done daily, weekly, monthly or even more rarely. At the same time as the above mentioned parameters are recorded a visual inspection of the transformer for leakages and cracks in bushings should be performed.

Periodic analysis of the oil in a transformer (oil condition monitoring) is by far the most widely used method for monitoring the general condition of a transformer. The condition of the oil and in particular, of the transformers insulation systems, can be determined by taking oil samples from the transformer for dissolved gas analysis (DGA) and other tests. The tests are comprehensively described for example, in the IEC Standard 60296 and the Guides 60422 and 60567. The presence of an incipient fault in a transformer will normally be detected by this means. Though, the interpretation of the fault mechanism and its location could be more difficult to determine. [Draft IEC 61378-3 Converter transformers - Part 3: Application guide].

Normally oil samples are taken when the transformer is energised and necessary safety precautions should be taken. The frequency of how often the oil samples should be taken will vary depending on the importance of the transformer. The most common frequency for oil condition monitoring is annually. When there is suspicion of an incipient fault in progress, the oil samples should be taken more frequently, e.g. every three months.

Improvements in the test procedure and analysis have occurred from time to time as the laboratory test equipment and the understanding of the chemical processes occurring in transformers and their analysis improve. An example of this is the measurement of the furfuraldehyde (FFA) content in transformer oil samples. The magnitude of the FFA constituent present in transformer oil samples is an important factor for assessing the ageing of the transformer insulation and indirectly offers an assessment of transformer life expectancy [Draft IEC 61378-3 Converter transformers - Part 3: Application guide].

Off-line condition monitoring takes place during a transformer outage, for maintenance or when an outage has occurred as the result of a transformer or network fault. Tests are on the transformer at site with the transformer de-energised.

The general condition of the transformer and of the insulation systems can be determined by taking oil samples from the transformer for dissolved gas analysis (DGA) and other tests, as described above.

In addition, specific site tests can be performed to determine the electrical and mechanical status of the transformer. The parameters that can be measured and used for this purpose include: [draft IEC 61378-3 Converter transformers - Part 3: Application guide].

- Winding resistances
- Magnetising currents
- Impedance voltages
- Dielectric loss factor
- Insulation resistance, including core and yoke clamps to earth,
- Inter-winding and winding to earth capacitance measurements.
- Dielectric response, measurement of moisture in solid insulation.

All the above tests are non-invasive with the exception possibly of the core insulation resistance measurements. Unless the core and clamps earthing connections have been brought out for external grounding, these particular tests may have to be made by opening the transformer to obtain access to the connections."

9.3.4. Inspection in energised condition

Inspection during operation shall only be performed after taking safety measures into consideration as applicable:

- If there is a maximum indicator on the thermometer the maximum temperature should be recorded,
- Oil levels, transformer, tap-changer,
- Check oil / water flow,
- Pressure gauges, leakage detectors,
- Surge arrester counters,
- Motor drive units counters,
- Surge arrester leakage currents,
- OLTC pressure oil filter manometers,
- Inspection for contamination, especially on bushings,
- Inspection of surface condition,
- Dehydrating breather. The silica gel shall be changed when approx. 2/3 of the silica gel has changed from blue to red colour (old type), or from pink to white, respectively. (Conservator type only),
- Inspection for leakages,
- Irregular noise from transformer, oil pumps, motors and cooling fans equipment
- Other irregular conditions; alarms, trips etc.
- Maintenance carried out

9.3.5. Inspection in de-energised condition

After the transformer is disconnected and properly earthed, inspection in de-energised condition may be performed. In addition to the items listed in section 9.3.4 it is possible to inspect items that not are visible in energised condition, typically equipment located on the transformer cover. Further, if necessary, internal inspection of the transformer may be performed after draining the oil.

9.4. MAINTENANCE

9.4.1. General

The primary purpose of transformer maintenance is to ensure the internal and external parts of the transformer and accessories are kept in good condition and "fit for purpose" and able to operate safely at all times. A secondary and equally essential purpose is to maintain a historical record of the condition of the transformer [draft IEC 61378-3 Converter transformers - Part 3: Application guide].

Transformer maintenance can be done periodically or as condition based maintenance. The latter is usually the most economical way of doing maintenance. Recommended maintenance are then done based on one or more of the following; inspections, analysis of oil samples, electrical measurements, test of equipment, measurement of temperatures by using a heat sensitive camera, monitoring (off-line and/or on-line).

9.4.2. Maintenance in energised condition

For personal safety reasons, only a limited amount of maintenance activities should be performed on the transformer when it is in operation. When necessary safety precautions have been taken the following maintenance can be done in energised condition:

- Inspection for leakages, cracks in porcelain bushings, check of auxiliary equipment etc.
- Check drying material in the dehydrating breather. (Conservator type only)
- Measurement of temperatures of joints, bushings etc. by using a heat sensitive camera
- Oil samples (Conservator type only).

9.4.3. Maintenance in de-energised condition

Before starting maintenance work, the transformer has to be disconnected from the network and earthed. When the circuit breaker and the isolator have been opened, they shall be locked in open position to prevent inadvertently closing during maintenance work.

Items to be considered are:

- Bushing gaskets; if leaks occur, tightening usually will help, if the gasket has lost its elasticity, it must be replaced. The reason for loss of elasticity could be excessive heating or aging,
- Cover gaskets, valves and gaskets of the tap changer. If there are leakages, bolt tightening will often help,
- Welded joints. Leaking joints can be repaired only by welding. A skilled welder and a welding instruction are required. Contact ABB for further instructions,
- Cleaning contaminated bushings (cleaning agent e.g. methylated spirit),
- Cleaning glasses on gas relay, thermometer and liquid level indicator,
- Functional inspection and testing of applicable accessories,
- Move tap changer through all positions a few times, all types of tap changers,
- Liquid sampling from bottom drain valve for larger units as required,
- Check drying material in the dehydrating breather. (Conservator type only),
- Amend surface treatment defects,
- Oil and insulation maintenance, drying and reclaiming, see section 9.4.5 page 132,
- Tap-changer maintenance, see sections 9.4.7 page 133 and 9.4.8 page 133,
- Inspection and maintenance on the active part should not be performed unless there are unambiguous indications of defects.

In addition, for dry-type transformers:

- Inspection and e.g. vacuum cleaning as required,
- Humidity removal,
- Tightening winding supports.

In heavily contaminated installations more frequent inspections may be needed.

9.4.4. Investigation of transformer disturbances

If, during operation, the protective equipment of the transformer gives an alarm or trips the transformer from the network, one should immediately investigate the reason for it. Studies may reveal whether it is a question of transformer damage or some other disturbances in the system.

9.4.4.1. Fault localisation advice, dry type transformers

For oil type transformers see section 9.4.4.2 for further information. For dry-type transformers, see table below in addition:

SYMPTOMS	PROBABLE CAUSES	SOLUTIONS
Low insulation resistance	Presence of humidity on surface of windings.	Clean with dry air. Ventilate.
	Contamination. Ageing.	Clean. Contact ABB.
The automatic protection device trips as soon as the transformer is energized	Windings. Defective windings.	Contact ABB.
	Tap changer or bolted links. The primary voltage does not coincide with the position or connection.	Check that the position or connection comply with the primary voltage.
	Fuses blows. Fuses incorrectly calibrated	Change fuses. Consider different rating
	Protection relays. Timing and/or current is incorrectly adjusted.	Check timing and current setting.
Unexpected secondary voltage	Primary voltage. Absence of primary voltage.	Check installation and contact the electricity utility.
	Tap changer or bolted links. incorrectly positioned or connected.	Change position or connection.
	Winding rupture.	Contact ABB.
Non-symmetrical voltages on the secondary side	Bolted links incorrectly connected in one of the phases.	Check the connections. Check installation and contact the electricity utility.
	Fuse has blown in one phase	Change fuse.
	Winding rupture	Contact ABB.
	L.V. installation Non-symmetrical load on the secondary side.	Check L.V. installation.
	No voltage applied in one of the phases on the primary side	Contact the electricity utility
Spurious triggering during operation	Triggering and alarm incorrectly set. Incorrect thermometer operation.	Check settings. Check thermometer
	Defect Pt100 sensors or thermistors.	Check sensors or thermistors.
	Fuse Blown fuse	Change fuse.
	Relays Incorrect timing.	Check timing.

SYMPTOMS	PROBABLE CAUSES	SOLUTIONS
Triggering of the overcurrent relay or blown HV fuses during operation	Short circuit in the system on the secondary side	Remove the failure in the system
	Perforation of insulating material.	Contact ABB
Triggering of differential relay during operation	Failure in the transformer	Contact ABB
	Failure in current transformers feeding the relay	Check current transformers
Abnormal operating temperature.	Insufficient ventilation. High ambient temperature.	Check ventilation of premises. Consider installation of cooling fans
	Transformer overloaded	Consider load reduction or installation of a transformer with higher power rating
	Local heating at the transformer terminals	Clean contact surfaces and retighten
	Excessive cable heating	Check the current-carrying capacity of the cable. Consider installation arrangement and the size of the cable.
High voltage to earth	Earth failure on one phase	Remove failure
High acoustical sound level	Supply voltage higher than presupposed	Change bolted links connection.
	Loose accessories or elements	Retighten.
	Reflection from walls and other elements.	Install sound damping panels. Place the transformer in non-parallel direction to the walls. Use damping pads below the transformer
	Low frequency	Contact electricity utility
Smoke	Insulation failure	Contact ABB

NOTE: Contact specialists before inspection, adjustment and repair of vital parts.
Observe guarantee conditions.

9.4.4.2. Fault localisation advises oil immersed transformers

The table below includes all types of oil immersed transformers.

SYMPTOMS	PROBABLE CAUSES	SOLUTIONS
Low insulation resistance	Earth fault. Oil deficiency	Contact ABB.
Unexpected secondary voltage	Primary voltage. Absence of primary voltage.	Check installation and contact the electricity utility.
	Tap changer or bolted links incorrectly positioned or connected.	Change position or connection.
	Winding rupture.	Contact ABB.
	Blown fuse in one phase	Change fuse

SYMPTOMS	PROBABLE CAUSES	SOLUTIONS
Non-symmetrical voltages on the secondary side	Bolted links incorrectly connected in one of the phases.	Check the connections. Check installation and contact the electricity utility.
	Winding rupture	Contact ABB.
	L.V. installation	Check L.V. installation.
	Non-symmetrical load on the secondary side.	
Triggering of the over-current relay	No voltage applied in one of the phases on the primary side	Contact the electricity utility
	Short circuit in the system on the secondary side	Remove the failure in the system
Triggering of differential relay during operation	Winding rupture	Contact ABB
	Internal failure in the transformer	Contact ABB
Spurious triggering during operation	Failure in current transformers feeding the relay	Check current transformers
	Triggering and alarm incorrectly set. Incorrect thermometer operation	Check settings. Check thermometer
	Defect Pt100 sensors or thermistors.	Check sensors or thermistors.
	Relays incorrect timing.	Check timing.
Abnormal operating temperature measured by thermography.	Short circuit in the control system on the secondary side	Remove the failure in the control system
	Local heating at the transformer terminals	Clean contact surfaces and retighten
Winding and/or Top-oil thermometer alarm and/or trip	Excessive cable heating	Undersized cables
	Insufficient ventilation. High ambient temperature.	Check ventilation of premises. Consider installation of cooling fans
	Transformer overloaded	Consider load reduction or installation of a transformer with higher power rating
	Reduced oil, water or air circulation	Check oil, water and air circulation
	Too high oil temperature	Reduce load.
	Too high water temperature	Reduce load.
Measurement of unexpected voltage to earth.	Earth failure on one phase	Remove failure
High acoustical sound level	Supply voltage higher than presupposed	Reduce supply voltage or change position on tapchanger
	Loose accessories or elements	Retighten.
	Reflection from walls and other elements.	Install sound damping panels. Place the transformer in non-parallel direction to the walls. Use damping pads below the transformer

SYMPTOMS	PROBABLE CAUSES	SOLUTIONS
	Low frequency	Contact electricity utility
Oil flow trip	Oil circulation too low	Open valves in oil circuit
	Oil pump protection	Check oil pump and protection
Buchholz-gas relay alarm	Gas-bubbles caused by local overheating	De-energize the transformer. If the captured gas is inflammable: Carry out dissolved gas analysis (DGA) Contact ABB
	Gas-bubbles caused by incomplete bleeding	If the captured gas is not inflammable: Bleed the transformer properly and energize.
Buchholz-gas relay trip	Arcing in active part	Carry out dissolved gas analysis (DGA) Contact ABB
	Oil level too low	Adjust oil level and repair leakages. Welding on the transformer is only allowed if the transformer is filled by oil / inert gas (nitrogen)
Oil level indicator: Alarm high level or Trip low level	Incorrect oil level.	Adjust oil level. Repair leakages if any. Welding on the transformer is only allowed if the transformer is filled by oil / inert gas (nitrogen)
Water flow switch / indicator alarm	Too low water flow	Increase water flow, clean water circuit / cooler
Pressure differential relay alarm	Pressure difference oil / water less than 0.03 bar	Reduce water pressure, check water flow, clean water circuit / cooler
Leakage detector alarm	Leakage in cooler	Repair / change the cooler
On load tap-changer protective relay trip	Sudden pressure rise tap-changer compartment	Inspection / repair of tap- changer diverter switch
On load tap-changer out of step trip	Operation of tap-changer failed	Check tap-changer, interlocking and synchronism
Pressure relief device trip	Sudden pressure rise transformer	Carry out dissolved gas analysis (DGA) Contact ABB
Gas monitoring alarm	Gas-detection	Carry out dissolved gas analysis (DGA) Contact ABB.

NOTE: Contact specialists before inspection, adjustment and repair of vital parts.
Observe guarantee conditions.

9.4.4.3. Recording of disturbances

- Date and time of the occurrence,
- Data for installed overvoltage protection,
- Network data, were connections or other relevant things made when the disturbance took place; what was the loading like; possible relay operations which took place elsewhere in the network (e.g. earth fault relay),
- Weather data (thunderstorm, rain, etc.),
- Is the gas relay filled with gas: colour and quality?
- Is oil sooty?
- Thermometer readings,
- Were coolers or tank damaged?
- Are there visible marks of arcing on e.g. the bushings, cover or conservator?
- In case of dry-type transformers, are there humidity, contamination or visible marks of arcing on windings, cleats and leads?
- Gas-in-oil analysis for LDT units and power transformers?
- Any other observation.

9.4.4.4. Function of transformer protective equipment

Operation of some protective equipment such as gas relay or differential relay does not always mean that the transformer is damaged.

The gas relay can operate for example when:

An air bubble has been left under the transformer cover. An air bubble is colourless and odourless.

A short-circuit current has passed the transformer. No gas bubbles.

However if the gas has colour or smell, the transformer is damaged.

9.4.4.5. Measurements

In addition to the above instructions, the following inspection measurements can be carried out:

- Insulation resistance.
To obtain reliable results, the insulators have to be dry, clean and overvoltage protection (surge arresters, RC-networks) has to be disconnected from the transformer.
- No-load current measurement by means of a variable low voltage source.
The voltage during measurement should gradually be increased. The measured current should be compared with the no-load current measured in the delivery test.
For higher voltages on the low-voltage side of the transformer the measured current will be in the range of a few milliamperes for a sound transformer,
- Voltage ratio,
- DC resistances of windings should be compared with the DC resistance measured during delivery test. The temperature when the measurements were made must be considered.

9.4.5. Transformer liquid and insulation

The task of oil in a transformer is to act as an electrical insulation and to transfer heat from the transformer's active parts into coolers. Oil acts as a good electrical insulation only as long as it is satisfactorily dry and clean.

Moisture balance between the oil and the solid insulation implies that most of the moisture will gather in the paper insulation.

Moisture in insulation is one of the dominant ageing accelerators. It is recommended to dry the insulation when the moisture exceeds a certain level. Drying of the insulation and oil is recommended for large distribution and power transformers since this can be technically and economically motivated. Equipment for drying transformers at site is available and the residual moisture in the insulation will be less than 1% after drying with low frequency heating equipment. During drying the transformer has to be de-energised. Drying time can vary from one to two weeks depending on the transformer size, amount of insulation and initial moisture level in the insulation.

Testing of oil in transformers should normally be performed 12 months after filling or refilling, subsequently annually on large distribution and power transformers. ABB offers different tests and analyses of oil samples depending of transformer type, size, service record and strategic importance for safe electricity supply.

Testing of oil in on load tap changers must be performed according to the tap changer supplier's recommendations.

To take oil samples from hermetically sealed transformers is normally not necessary, and should only be performed after consultation with ABB. The oil in this type of transformers is not in contact with the atmosphere, and less exposed to moisture.

Especially for large distribution and power transformers, oil regeneration/reclaiming of oil may be technically and economically motivated. Reclaiming implies filtering, de-gassing, removal of ageing by-products and addition of inhibitor if required. Reclaiming of oil is performed with the transformer in service (operation). The transformer is only de-energised for a few hours when the equipment is connected and disconnected from the transformer. If the oil is in good condition, except from particles present in the oil, filtering can be recommended for removal of the particles.

Often it is recommended to do both drying and reclaiming on the same transformer. Done at the right time, recommended by the supplier, i.e. before the degradation of oil and insulation has gone too far, the lifetime of the transformer can be extended with several years.

9.4.6. Bushings and joints

The porcelain insulators of transformer bushings ought to be cleaned during service interruptions as often as necessary. This is particularly important for places exposed to contamination and moisture.

Methylated spirit or easily evaporating cleaning agents can be used for cleaning.

The condition of external conductor and bus bar joints of transformer bushings shall be checked at regular intervals because reduced contact pressure in the joints leads to overheated bushings etc. and may cause the adjacent gasket to be destroyed by the heat. A heat sensitive camera can be used to check the temperatures in joints, bushings etc.

Maintenance of HV condenser bushings shall be performed according to the instructions given by the bushing supplier.

9.4.7. Off-circuit tap changer

The transformation ratio can be adjusted with an off-circuit tap changer when the transformer is not energised.

The control shaft of the off-circuit tap changer is brought through the cover or the tank wall. The shaft end is provided with a handle, position indicator and locking device. When the tap changer is turned the locking device must be secured, because that assures that the off-circuit tap changer has been set to operating position.

Off-circuit tap changers do normally not require regular maintenance, but it is recommended that the off-circuit tap changer is moved from one extreme position to the other a few times during service interruption. This is necessary especially when the tap changer is moved infrequently. Moving from one position to another is performed either manually by a hand wheel or by a motor drive unit.

Total expected lifetime depends on the number of operations, normal current etc. Inspection / maintenance of tap-changers must only be carried out by trained and experienced personnel. See supplier's documentation provided.

For dry-type transformers the off-circuit tap changing is generally done by means of bolted links.

9.4.8. On-load tap-changer

Maintenance of on load tap-changer shall be performed according to the instructions given by the supplier of the tap-changer.

Reference should be made to IEC 60214 (Tap-changers) and IEC 60542 (Application guide for on-load tap-changers) and especially to the tap-changer manufacturers operation and maintenance instructions. In addition, it is strongly recommended that only suitably trained personnel should undertake OLTC examination and maintenance [IEC 61378-3 Convertor transformers - Part 3: Application guide].

On-load tap-changers have to be maintained regularly. Maintenance interval and total expected lifetime depends on number of operations, normal current, if oil filtering unit is provided etc.

9.4.9. Motor drive unit

Motor drive units have to be maintained regularly. Maintenance interval and total expected lifetime depends on number of operations. Only trained and experienced personnel must carry out maintenance of motor drive units. See supplier's documentation provided.

9.4.10. Oil filtering unit

The paper filter in the oil-filtering unit for the on-load tap-changer has to be changed when pressure loss has reached approximately 4 bars on the pressure gauge. See the supplier's documentation.

9.4.11. Coolers

Coolers are cleaned by means of e.g. brushing inside the water tubes or air side vacuum cleaning when necessary. Need for cleaning is indicated by increased pressure loss, decreased temperature-difference oil/water/air in/out, increased transformer temperature, decreased water flow etc. See the supplier's documentation.

9.4.12. Liquid conservator with rubber diaphragm

The system consisting of oil conservator with rubber sack does normally not require any other maintenance than inspection of the silica gel breather. The silica gel shall be changed when approx. 2/3 of the silica gel has changed from blue to red colour (old type of silica gel) or from pink to white, respectively.

9.4.13. Gaskets

The gaskets of the cover and flanges, as well as between bushings and cover, are usually made of liquid resistant vulcanised cork sheet, nitrile rubber or silicone sealant.

If the gaskets are leaking, leaks can usually be sealed by tightening the screws (bolts).

When these gaskets have to be replaced, it is recommended to contact ABB.

Liquid resistant rubber rings are used as gasket for bushing bolts, shafts and spindles. All these gaskets can be tightened and replaced from outside the tank.

When tightening the gaskets special care must be taken to prevent the breaking of screws (bolts) or the gasket "floats away" (if not in a groove) caused by the heavy pressure. In particular stud nuts must be tightened very carefully.

9.4.14. Dry-type transformers

Dust and dirt on the transformer leads to reduced dielectric strength and cooling due to different environmental conditions where ventilated dry type transformers are installed. A periodic program for cleaning should be established for each installation. Horizontal surfaces should be cleaned with a vacuum cleaner. Coils cooling ducts should be cleaned using dry compressed air or nitrogen (maximum pressure 3 bar).

If the transformer is installed in an enclosure, the enclosure should be cleaned like switchgear cubicles. Dust accumulation on the enclosure ventilation opening is an indication that an internal inspection should be made.

In addition to cleaning the following should also be carried out during the inspection:

- The condition of external bolted electrical connections shall be checked and retightened.
- Loose winding clamps shall be retightened.
- The function of all warning devices shall be checked.
- Cooling fans shall be cleaned like the transformer. Afterwards, check their function and operation.

9.4.15. Surface protection

9.4.15.1. Painted surfaces

When repairing damaged paint, the points to be repainted should be cleaned from rust, dirt and grease before priming with a zinc rich primer prior to top coat paint. The final paint thickness should at least be equal to the original paint thickness.

By major paint damages contact with a specialised surface coating company is recommended.

9.4.15.2. Zinc coated surfaces

Zinc coated surfaces have a self-repairing, passivating, characteristic. Small damages as scratches do normally not need repairing. Larger areas, above 50 mm², may need repair. After thoroughly cleaning apply zinc-rich (between 65-69% zinc by weight, or >92% by weight metallic zinc in dry film) paint to at least the same thickness as the original zinc coating. Do not remove any original zinc during cleaning. The paint may be one-component (preferred) or two-component.

10. DISPOSAL AFTER USE

Scrapped transformers may harm the environment, they may, however, also represent a value if treated correspondingly.

Some transformer owners prefer to scrap used transformers themselves.

If not, ABB have agreements with local waste processing plants and may dispose of used transformers taking sustainable development into consideration.

Material disposal technology is continuously improving, thus the salvage value of a transformer is expected to increase in the future. Transformers acquired today may after service life, e.g. 20 years, represent a higher value than those scrapped today. It is also expected that materials which today are not recyclable may be treated differently in the future.

10.1. LOCAL REGULATIONS

Local regulations shall always be adhered to in disposing used transformers. Local authorities may give guidance; also Internet community home pages may give advice.

If in doubt the local ABB Company can assist.

10.2. REUSE

Transformers contain valuable materials, which may be reused either as is or after reprocessing.

Examples are:

- Copper,
- Aluminium,
- Oil,
- Steel.

Insulation material, pressboard and paper, represent energy.

10.3. LANDFILL

Materials not re-circulated go to landfill or energy production. The landfill portion of the transformer should be minimized.

10.4. LIFE CYCLE ASSESSMENT (LCA)

The environmental impact of transformers may be divided into five life cycle categories:

1. Raw material extraction, manufacturing and transport
2. Transformer production
3. Transport to site
4. Energy losses during service
5. Disposal after use

LCA calculations show that categories 1, 2 and 3 are negligible compared to 4.

A part of category 1 is regained during disposal, provided reuse of materials or energy extraction.

Life cycle assessment shows that the dominating environmental impact during a transformers life is energy losses during service. The total losses consist of load losses and no load losses, both are significant. The relation between load and no load losses depends on the transformer loading.

The lifetime energy losses are one of the reasons why ABB recommends an energy-effective transformer layout, see section 4 page 62.

10.5. PCB-Contaminated oil

PCB was used in many ways and was included in several different products, including transformer and condenser oil, however it is harmful to the environment and develops cancer-causing dioxides during normal combustion. The use of PCB is now prohibited.

Not all ABB transformer manufacturers used PCB, and those who did, stopped using it long before the factories were acquired by ABB.

ABB can assist in the disposal of PCB-contaminated oil.

11. PHYSICAL FUNDAMENTALS

11.1. INTRODUCTION

A transformer is a static device with two or more windings that are linked to each other by means of a strong magnetic field. Transformers are designed for specific purposes, such as the measurement of voltage and current, or the transfer of signals or electric power. The design requirements of transformers depend on the application. In measurement transformers, the quantity measured must be transferred from the primary circuit to the secondary as exactly as possible, while in signal transformers the signal must be transferred with a minimum of distortion.

This text concentrates on power transformers, where the main requirement is that it shall transfer a certain amount of electric power at a constant frequency while the voltage is being changed from one level to another with a minimum of power losses.

11.2. CHOICE OF SYSTEM VOLTAGE

Large power stations where the electric energy is generated are often situated far away from the numerous places where the electric energy is consumed. The need for high voltage levels in electric power transmission is illustrated in the following.

The power loss p in a 3-phase transmission line with a resistance R per phase and a current I flowing in each phase is:

$$p = 3 \cdot R \cdot I^2 \quad (W) \quad (1)$$

At a system voltage U the transmitted active power is:

$$P = \sqrt{3} \cdot U \cdot I \cdot \cos \varphi \quad (W) \quad (2)$$

Equation (2) can be rewritten as:

$$I = \frac{P}{\sqrt{3} \cdot U \cdot \cos \varphi} \quad (A) \quad (3)$$

Inserted in the equation (1) gives:

$$p = P^2 \frac{R}{U^2 \cdot \cos^2 \varphi} \quad (W) \quad (4)$$

Equation (4) indicates that the power loss in the line is proportional to the square of the transmitted active power and inversely proportional to the square of the system voltage.

In other words, the power loss will be lower when the system voltage is increased.

The choice of system voltage is a matter of economic balance. A high system voltage reduces the transmission losses, but on the other side it requires more expensive lines, cables and transformers.

Several hundreds of kilovolts are used for lines transporting large quantities of electric power over long distances. Closer to the consumers the power is distributed at lower voltage levels. The voltage is taken down in several steps. While generator transformers are step-up transformers, the distribution transformers are normally step-down transformers. The power rating of distribution transformers is usually lower the closer to the consumer the transformers are situated.

11.3. BASIC PHYSICS OF THE TRANSFORMER

The function of a transformer is mainly based on two physical phenomena.

One of them is the electromagnetic induction, which was discovered by Faraday in the 1830's. The induction law was formulated by Neumann in 1845.

Consider a loop of a conducting material enclosing a magnetic field Φ . If a change $\Delta\Phi$ takes place during a short time-interval Δt , a voltage will be induced which will drive a current around in the loop. The induced voltage u_i is proportional to the quotient $\Delta\Phi / \Delta t$, or more correctly written on differential form:

$$u_i = \frac{d\Phi}{dt} \quad (V) \quad (5)$$

This is the scalar value of the induced voltage. To indicate also the direction of the induced voltage, the induction law is written as:

$$\bar{u}_i = - \frac{d\Phi}{dt} \quad (V) \quad (6)$$

where the minus sign indicates that u_i has the direction that it will drive a current through the loop, which sets up a magnetic field with the opposite direction of the change $d\Phi$. In other words, the induced current strives to resist any change in the magnetic field. When the flux increases, the induced current has the direction that gives a flux with a direction opposite the direction of Φ . When the flux decreases, the induced current has the direction that gives a flux with a direction in phase with Φ .

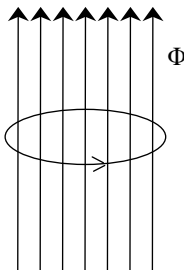


Figure 11-1

If the loop is replaced by a coil with N number of series-connected turns, the same induced voltage will take place in each of the turns. The voltage induced in the whole coil will then be:

$$\bar{u}_i = -N \cdot \frac{d\Phi}{dt} \quad (V) \quad (7)$$

The other physical phenomenon is that a conductor carrying an electrical current is surrounded by a magnetic field.

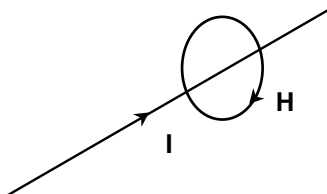


Figure 11-2

To create a magnetic field that varies in time in a transformer a sinusoidal voltage is applied to the primary winding which creates a magnetising current.

The windings are made as concentric shells around a central core of laminated steel plates, which is formed as a closed loop for the magnetic field. Due to the magnetic properties of the steel the magnetic flux will be several thousand times higher than it would have been without the steel core, which makes the magnetic coupling between the windings strong.

When the terminals of the secondary winding are open, the relation between the applied voltage on the primary side and the output voltage on the secondary side is the same as the relation between the number of turns in the primary winding and the secondary winding respectively:

$$\frac{U_1}{U_2} = \frac{N_1}{N_2} \quad (8)$$

or

$$U_2 = U_1 \cdot \frac{N_2}{N_1} \quad (V) \quad (9)$$

When the secondary winding is loaded, the voltage ratio may differ considerably from the turn ratio (see 6.5.), while the ratio between the primary and secondary currents fulfils the equation:

$$I_1 \cdot N_1 = I_2 \cdot N_2 \quad (10)$$

with a deviation of one percent or less.

11.4. EQUIVALENT DIAGRAM

A simple equivalent diagram for the transformer can be drawn based on two measurements on the transformer, one in no load and one in short-circuited condition.

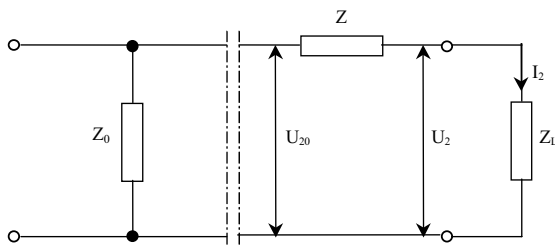


Figure 11-3

In no load condition (open secondary terminals) the total magnetising current and the active power consumption are measured at rated voltage. The current has one dominant inductive component and one smaller active component. These can be calculated from the measurements, and the real and the imaginary components of transformer's no load impedance Z_0 can be found. This impedance is not constant but will vary non-linearly with the applied voltage due to the non-linearity of the magnetisation curve. The real part of Z_0 represents the no load losses.

The other impedance in the diagram, Z , is found by short-circuiting the secondary terminals and applying a voltage at the primary side. The current in the windings during this measurement shall be equal to the rated current. To achieve this current an applied voltage of just a fraction of the rated voltage will be sufficient. This voltage is called the short-circuit voltage and is usually expressed as a percentage of the rated voltage. The impedance of the circuit is given by the quotient of the short-circuit voltage divided by the rated current. The circuit is a parallel connection of Z_0 and Z . Because $Z_0 \gg Z$ the impedance of the parallel connection is equal to Z with a negligible difference. The real part of Z represents the load losses of the transformer, and the imaginary part is attributed to the magnetic leakage field. That is the part of the magnetic field, which is situated outside the core.

11.5. VOLTAGE RATIO AND VOLTAGE DROP (OR RISE)

The voltage ratio of a transformer is normally specified in no load condition and is directly proportional to the ratio of the number of turns in the windings.

When the transformer is loaded, the voltage on the secondary terminals changes from that in no load condition, depending on

- the angle ϕ between the voltage on the secondary terminals of the transformer U_2 and the secondary current I_2
- the value of the secondary current I_2
- the short-circuit impedance of the transformer Z and its active and reactive components, r and $\pm jx$ respectively

At no load the secondary voltage is U_{20} . With the load Z_L connected, the voltage at the secondary terminals changes to U_2 . The corresponding vector diagram is shown in Figure 4. In the following considerations symmetrical loading is assumed. The influence of the small magnetising current (usually in the magnitude of 1% of the rated current) is negligible.

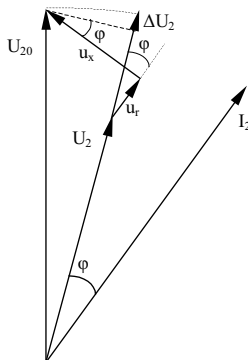


Figure 11-4

From the vector diagram in Figure 11-4 the following relationship appears:

$$\Delta U_2 = I_2 \cdot r \cdot \cos \varphi + I_2 \cdot x \cdot \sin \varphi + U_{20} - \sqrt{U_{20}^2 - (I_2 \cdot r \cdot \sin \varphi - I_2 \cdot x \cdot \cos \varphi)^2} \quad (V) \quad (11)$$

ΔU_2 is the voltage drop, the arithmetic difference between U_{20} and U_2 . u_r and u_x are the active and the reactive short-circuit voltages at rated current related to the rated voltage U_{20} .

To calculate the relative voltage drop at any relative loading n (see (13)) equation (11) can be rewritten as

$$\frac{\Delta U_2}{U_{20}} = n(u_r \cos \varphi + u_x \sin \varphi) + 1 - \sqrt{1 - n^2(u_r \sin \varphi - u_x \cos \varphi)^2} \quad (12)$$

$$n = \frac{I_2}{I_{2N}} \quad (13)$$

Example: $n = 1$ $u_r = 0,01$ $u_x = 0,06$ $\cos \varphi = 0,8$ inductive

$$\frac{\Delta U_2}{U_{20}} = 1 \cdot (0,01 \cdot 0,8 + 0,06 \cdot 0,6) + 1 - \sqrt{1 - 1^2 \cdot (0,01 \cdot 0,6 - 0,06 \cdot 0,8)^2} = 0,045 \quad (14)$$

$$\Delta U_2 = 0,045 \cdot U_{20} \quad (V) \quad (15)$$

$$U_2 = U_{20} - \Delta U_2 = (1 - 0,045) \cdot U_{20} = 0,955 \cdot U_{20} \quad (V) \quad (16)$$

In other words, when a transformer with these values for u_r and u_x is loaded with rated current with a power factor of 0,8 inductive the voltage on the secondary terminals decreases to 95,5% of the voltage at no load.

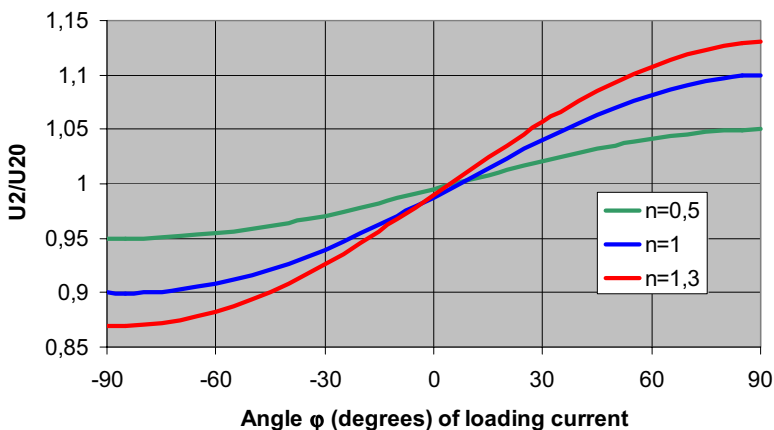


Figure 11-5

Figure 11-5 shows an example of how the secondary voltage varies with various angles of ϕ and load currents for the particular values $u_r = 0,74\%$ and $u_x = 10\%$. Negative angles of ϕ mean lagging (inductive) load current. Positive angles of ϕ mean leading (capacitive) load current.

Note that at angle ϕ above a certain positive value the secondary voltage increases compared to voltage at no load.

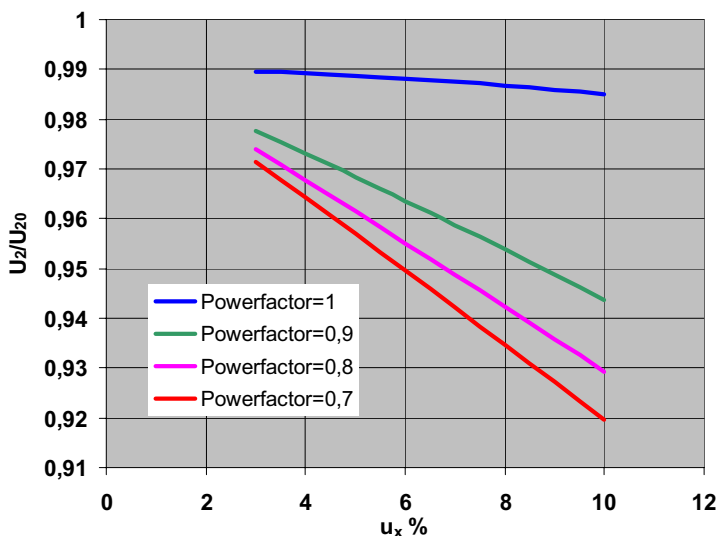


Figure 11-6

Figure 11-6 shows another example of how the secondary voltage may vary at various values of the short circuit reactance u_x and of $\cos\phi$. In general the secondary voltage decreases with increasing u_x . Note that for example at $u_x=10\%$ and $\cos\phi=0,8$ the secondary voltage has dropped to 93% of the no load voltage.

magnetic flux proceed towards smaller negative values, they follow the curve from a to b. At point b the magnetising current is zero, but there is still remaining a magnetic flux in the core. This flux is called the remanent magnetic flux.

When proceeding further along the curve to the right in the diagram the magnetising force changes to positive direction. At point c the flux density in the core becomes zero. This value of the magnetising force is called the coercive force.

Increasing the magnetising force further from point c, a flux in the positive direction starts to flow in the core. At point d the current and the flux start to decrease. However, as these values decrease, they follow the curve to the left rather than to the right.

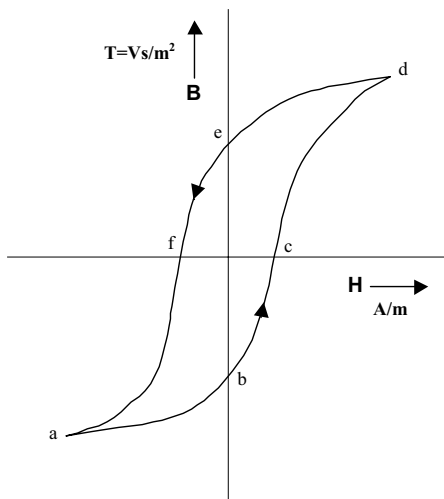


Figure 11-7

At point e the current has decreased to zero. And again there is a remanent flux floating in the core, this time with the opposite direction compared to the remanent flux at point b. Increasing the current now in the negative direction, the flux decreases further and becomes zero at point f. From point f on the flux changes direction and increases in the negative direction until it reaches point a. Now one cycle of the applied voltage is completed.

The physical explanation for the described course of events is, expressed in the following simplified way, a ferromagnetic material has numerous small magnets attached to its crystalline molecular structure. Within certain domains these magnets have the same orientation. In the original state of the material these domains are randomly orientated, and the magnetic field from each of them practically cancels each other so there is no resulting magnetic field.

If the material is placed in an external magnetic field, this will have an impact on the orientation of the domains. As the external field is increasing, more and more of the domains will change their direction so the direction of their magnetic field coincides with the direction of the external field.

If the external field gradually decreases, more and more domains will slide out of the orientation they obtained due to the external field. But when the external field has disappeared, there will still be a considerable number of domains, which remain in the same direction as they were under the influence of the foregoing external field.

Exposed to an increasing external field of opposite direction, more and more domains will change orientation. At a certain value of the external field, the orientation of the domains will be so mixed that there is no resulting magnetic field from them. Further increase of the external field will cause more and more domains to change their direction gradually so the direction of their magnetic field coincides with the new direction of the external field.

Due to the many magnetic domains that become unidirectional, the total magnetic field will be thousands of times higher than the original external field that directed the domains.

Reorientation of the domains is a gradual process that requires some time. This is the reason why the magnetic flux lags behind the magnetizing force, which the diagram in Figure 11-7 illustrates. This diagram is called the hysteresis loop. The word hysteresis comes from the Greek *hystereo* = lag behind.

The hysteresis loop illustrates also that the slope of the curve decreases with increasing magnetizing force. At a certain flux density the slope of the curve will become equal to μ_0 , the permeability of air.

This means that no further increase in the magnetic flux can be obtained from the ferromagnetic material. All the domains have now aligned their field with the external field. This is called magnetic saturation. For the best commercially available core material today the saturation flux density is slightly above 2,0 Tesla (Vs/m^2).

The permeability is equal to the slope of the hysteresis loop. Because this slope varies during a cycle of the applied voltage, the permeability is not a constant but varies during the cycle and varies also with the peak value of the flux density.

To turn the direction of the magnetic domains requires a supply of active energy. The required energy is represented by the area within the hysteresis loop, which has the unit of Ws/m^3 of core material. The supplied energy changes to heat, which increases the temperature of the core. One could imagine that there is friction present in the material when the domains turn around. The supplied energy appears as losses in the transformer. They are called hysteresis losses, and they are proportional to the frequency. At 50 Hz the hysteresis loop is run through 50 times per second. The hysteresis losses per second will then be 50 times the area of the loop. The loop can be displayed on the screen of an oscilloscope.

Materials with a narrow hysteresis loop, that is low coercive force, have low hysteresis losses.

As mentioned previously, the no load current is not sinusoidal.

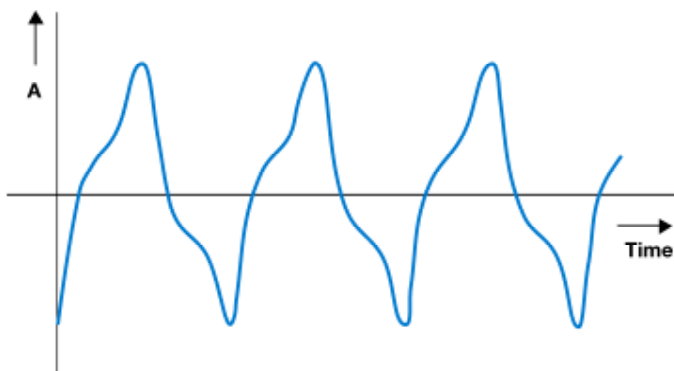


Figure 11-8

Figure 11-8 shows a typical shape of this current, which can be constructed from the hysteresis loop. It has a short peak value due to the low slope of the magnetising curves (the right and the left strings of the hysteresis loop) at high flux densities. It is non-symmetrical on the two sides of the peak value due to the width of the hysteresis loop.

The no load current measured at the delivery test and noted in the test report is the r.m.s.-value of the non-sinusoidal no load current. For three-phase transformers the average value for the three phases is noted.

Eddy current losses

Another component of the no load losses is the eddy current losses. The time-variable magnetic flux induces currents running in paths perpendicular to the direction of the flux. These currents produce losses in the core plates. These losses can be calculated by means of the following formula:

$$P_{\text{eddy}} = \frac{1}{24} \cdot \sigma \cdot \omega^2 \cdot d^2 \cdot B^2 \cdot V \quad (W) \quad (17)$$

where

σ is the conductivity of the core material
 ω is the angular frequency
 d is the thickness of the core plates
 B is the peak value of the flux density
 V is the volume of the core

The formula deserves some comments. It appears that the eddy current losses are proportional to the conductivity of the core material. In modern core plate a few percents of silicon is alloyed to reduce the conductivity and the eddy current losses. But if the silicon content exceeds a certain limit, the material will be difficult to roll, slit and cut.

The eddy current losses are proportional to the square of the thickness of the plates. The choice of plate thickness is a matter of economic balance between the capitalised value of the losses and manufacturing costs. In practice the thickness is normally within the range 0,23 – 0,30 mm.

Anomalous losses

For the sake of completeness there is a third component in the no load losses which is called anomalous losses that have been ascribed to a diffusion phenomena in the crystal grid of the material.

The traditional way to measure the specific total losses in core steel expressed in W per kg core steel has been by means of the Epstein frame. This is a quadratic frame made of the laminated core steel to be investigated. The method is described in IEC 60404-2 (1996-03) Magnetic materials – Part 2: Methods of measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame.

It is relatively laborious and time consuming to prepare the samples for the Epstein measurement. In order to establish a quicker method that facilitates measurements on a higher number of samples, single sheet testers were developed. This makes it possible to state average and variability values with higher statistical confidence.

In single sheet testers a magnetic field is created that is applied perpendicular to the surface of the sample sheet at one end, floats along the length of the sheet and goes out again perpendicular to the surface again at the other end. The method is standardised and described in IEC 60404-3 (2002-10) Ed. 2.1 Magnetic materials – Part 3: Methods of measurement of the magnetic properties of magnetic sheet and strip by means of a single sheet tester.

The no load losses in a transformer core in W per kg core steel will normally be higher than the values obtained from test samples in a laboratory. There are several reasons for this.

Modern low loss core steel is quite sensitive to mechanical strain and treatment. The large number of thin core plates must be kept together by means of a certain pressure, which also may be unevenly distributed along the core limbs and yokes. The joints between limbs and yokes where the flux direction changes may not be perfect due to tolerances in the manufacturing. Particularly the joints between limbs and the upper yoke are critical because the plates of the upper yoke are more or less forced down after the core is raised and the windings are assembled on the limbs.

Burrs at the edges of the core plates influence the losses unfavourably. The increase in losses in a real transformer core compared to the material measurements in laboratories is often expressed by means of a factor called the 'building factor'. This factor varies with the cross section area of the core and with the design as well.

Experienced manufacturers are normally able to predict the no load losses with not more than a few percent deviation from the measured losses. This is due to studies of the flux pattern in transformer cores and mathematical models derived from regression analysis of the measured losses of a large number of transformers.

Inrush currents

Inrush currents have sometimes been a problem from a protection point of view. Fuses have blown or relays have disconnected the transformer immediately after energizing. This may create the suspicion that there is something wrong with the transformer. An explanation of the phenomenon will be given in the following.

The magnitude of the inrush current is a statistical variable depending on where on the sinusoidal voltage curve the circuit breaker connects the transformer to the voltage source. The highest inrush current occurs when the circuit breaker connects the transformer when the voltage passes through zero.

When the circuit breaker disconnects the transformer from the voltage source, there will always remain a remanent flux in the core, unless the disconnection takes place exactly when the flux passes zero. The remanent flux will be a statistical variable. It will be at its maximum if the disconnection happens when the flux has its maximum. The polarity of the remanent flux may be positive or negative.

The induction law states that the induced voltage is proportional to the time derivative of the magnetic flux.

$$u = d\Phi/dt \quad (V) \quad (18)$$

This can also be seen the opposite way, the magnetic flux is the time integral of the voltage:

$$d\Phi = u \cdot dt \quad (Vs) \quad (19)$$

$$\Phi = \int u \cdot dt \quad (Vs) \quad (20)$$

Assuming that the voltage is sinusoidal and the integral is taken over the first half cycle of the voltage, that is from 0 to π , where 0 is the time when the circuit breaker makes and π is the time when the voltage changes direction:

$$\Phi = \int_0^{\pi} U \cdot \sin(\omega t) \cdot d(\omega t) = U(-\cos \pi - (-\cos 0)) = 2U \quad (Vs) \quad (21)$$

To compare this result with the situation when the circuit breaker makes at the peak value of the voltage, the integral is taken between the limits $\pi/2$ and π .

$$\Phi = \int_{\pi/2}^{\pi} U \cdot \sin(\omega t) \cdot d(\omega t) = U(-\cos \pi - (-\cos \pi/2)) = U \quad (Vs) \quad (22)$$

Equation (22) complies with the situation in continuous normal service.

From equation (21) it appears that the magnetic flux reaches a value, which is twice as large as it is in normal service if the circuit breaker makes when the voltage passes through zero. This means that the point of magnetic saturation in the core will be exceeded. The reactance of the transformer is then very low compared to the large reactance at normal flux. A high current will then be drawn from the energy source. This current will be of the same magnitude and character as a short-circuit current, and will cause considerable mechanical forces in the primary winding. The forces are proportional to the square of the current.

If the remanent flux Φ_r has the same direction as the flux calculated in the foregoing the total flux will be

$$\Phi_t = 2\Phi + \Phi_r \quad (Vs) \quad (23)$$

which makes the inrush current even higher.

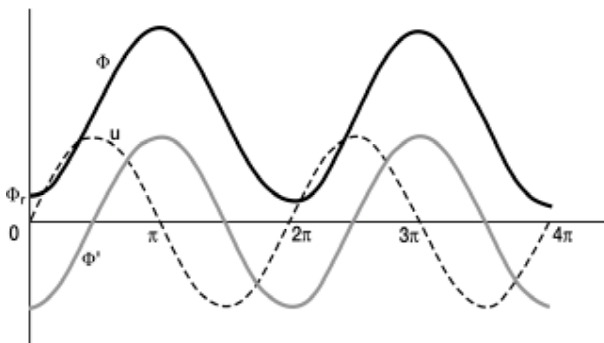


Figure 11-9

Figure 11-9 illustrates the situation. The light grey curve marked Φ' is the magnetic flux in the normal stationary condition.

When the voltage changes direction at π , the current will decrease. But at 2π the current will increase again. This course of events will continue with gradually decreasing peak values of the current. The influence of the original remanent flux will also gradually disappear. The number of cycles before stationary normal operation is reached ranges from less than 10 cycles for small transformers up to several minutes for larger transformers.

A sudden increased sound level that follows the same declining development as the magnetic flux can be heard.

The statistical probability that the absolute worst case will occur is not high. In most cases electrical connection between the two poles of the circuit breaker will be established before metallic contact between the poles takes place because of arcing between the poles. There is higher probability that such arcing will occur when the voltage difference between the poles is in the range of the voltage maximum than when this voltage difference is close to zero.

The short-circuit power of the feeding source has also influence on the magnitude of the inrush current. If the short-circuit impedance of the source is high, the inrush current will cause a voltage drop across this impedance which will reduce the voltage at the transformer terminals. It can also be noted that the worst case only occurs in one out of the three phases.

A characteristic of the inrush current is that it contains a second harmonic component because of asymmetrical half-cycles. Modern overcurrent relays and differential relays contain a control circuit that reduces the sensitivity of the relay when a second harmonic in the current exists. In that way a releasing signal from the relay to the circuit breaker is prevented during inrush current, which is a normal physical phenomenon and not a failure.

Inrush currents tend to be higher on modern transformers compared to transformers manufactured say 40 years ago. The reason is that modern low loss core steel allows higher flux densities in the core without unacceptable high core temperatures as a consequence.

11.8. LOAD LOSSES

The currents floating in the windings create losses due to the resistance in the windings. They are equal to RI^2 in each of the windings, where R is the direct current winding resistance and I the current through the winding.

The eddy current losses come in addition. The winding conductors are situated in a time-varying magnetic field due to the current floating in the conductors themselves. See Figure 11-10. This magnetic field creates eddy currents in the winding conductors. The consequence of the eddy currents is that the resulting current in the conductors is unevenly distributed in the cross section of the conductor, which in turn increases the losses.

The magnetic flux density varies also across the radial width of the winding. In a simple winding configuration of a two-winding transformer, where the windings are situated as two concentric shells, the flux density is highest at conductors nearest the duct between the shells. Consequently the losses and also the temperature will be highest in these conductors.

To avoid high eddy current losses the conductor dimension perpendicular to the magnetic flux lines must be kept small. Further tall and slim windings have lower eddy current losses than low and wide windings. However, in practise the design of a transformer is often a compromise between different considerations, like for example short-circuit impedance and space limitations.

Because of the magnetic leakage field additional losses arise in the tank and in metal details keeping the core and the windings firmly together.

The RI^2 losses increase with the temperature while the additional losses decrease with increasing temperature. The temperature that guaranteed losses shall be referred to is stated in the standards.

11.9. SHORT-CIRCUIT IMPEDANCE

Users have sometimes particular requirements regarding the short-circuit impedance. Such requirements may be determined by:

- parallel operation with existing units,
- limitation of voltage drop,
- limitation of short-circuit currents.

The transformer designer can meet the requirements in different ways:

- The size of the core cross-section. A large cross-section gives a low impedance and vice versa,
- A tall transformer gives a low impedance and vice versa.

For each transformer there is, however, a smaller range which gives the optimum transformer from an economic point of view, that is the lowest sum of the manufacturing costs and the capitalised value of the losses.

Regarding smaller distribution transformers a high degree of standardisation in the manufacturing may in certain cases constrain the designer's ability to meet the requirements.

Short-circuit impedance Z is often expressed as u_z in p.u. or in % according to the following formulas:

$$u_z = I_r \cdot Z / U_r \quad \text{p.u.} \quad (24)$$

$$u_z = 100 \cdot I_r \cdot Z / U_r \quad \% \quad (25)$$

Formulas (24) and (25) are valid for single-phase transformers, where I_r and U_r are rated values of current and voltage on either side of the transformer. For 3-phase transformers the nominator must be multiplied with $\sqrt{3}$.

Based on measured short-circuit voltage the value of Z_k expressed in ohm can be calculated from the following formula:

$$Z = u_{z\%} \cdot U_r / 100 \cdot I_r = u_{z\%} / 100 \cdot U_r^2 / S_r \quad \Omega \quad (26)$$

for single phase transformers and

$$Z = u_{z\%} \cdot U_r / \sqrt{3} \cdot 100 \cdot I_r = u_{z\%} / 100 \cdot U_r^2 / S_r \quad \Omega \quad (27)$$

for 3-phase transformers. S_r is the rated power of the transformer.

From formulas (26) and (27) it appears that Z expressed in ohm is different depending on which side of the transformer it is referred to, because the ratio U_r/I_r or U_r^2/S_r is different on each side of the transformer, unless the turn ratio is equal to 1.

It follows that

$$\frac{Z_1}{Z_2} = \left(\frac{U_{r1}}{U_{r2}} \right)^2 = \left(\frac{N_1}{N_2} \right)^2 \quad (28)$$

where the indices 1 and 2 refers to the two sides of the transformer. The relation between the short-circuit impedance *expressed in ohm* referred to the two sides of the transformer is equal to the square of the turn ratio or square of the rated voltage ratio.

Z has the active and reactive components R and jX . To find these components the load losses (P_L) are registered by means of wattmeters during the short-circuit measurement. Then

$$R = P_L / I_r^2 \quad \Omega \quad (29)$$

$$X = \sqrt{Z^2 - R^2} \quad \Omega \quad (30)$$

The real part of the short-circuit voltage is

$$u_r = \frac{R \cdot I_r}{U_r} \quad \text{p.u.} \quad (31)$$

$$u_{r\%} = \frac{R \cdot I_r}{U_r} \cdot 100 \quad \% \quad (32)$$

For three-phase transformers a factor $\sqrt{3}$ is inserted in the nominator. There is a simple relation between u_r , the load losses P_L and the rated power S_r of the transformer:

$$u_r = \frac{R \cdot I_r}{U_r} = \frac{R \cdot I_r^2}{U_r \cdot I_r} = \frac{P_r}{S_r} \quad \text{p.u.} \quad (33)$$

The relation $u_r = P_r/S_r$ is also valid for 3-phase transformers. The imaginary part of u_z can be calculated as

$$u_x = \sqrt{u_z^2 - u_r^2} \quad \text{p.u. or \%} \quad (34)$$

$$X = \sqrt{Z^2 - R^2} \quad \Omega \quad (35)$$

While X_0 is mainly linked to the magnetic field in the core, X is linked to magnetic leakage field, which mainly runs through the windings and the ducts between windings.

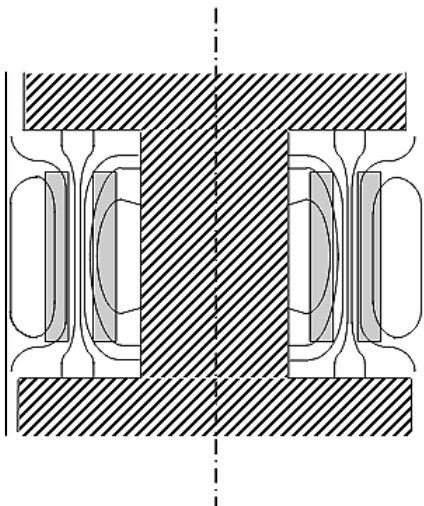


Figure 11-10

When the transformer is energized but not loaded, the practically the whole magnetic field goes in the core. When loading the transformer with a lagging current, a part of the magnetic field is drawn out from the core to the core window where the windings are situated. See Figure 11-10. The magnetic flux in the core becomes smaller. Typically for distribution transformers the high voltage is applied to the outer winding. The secondary low voltage winding is the inner winding where the voltage decreases.

If a capacitive load is added the resulting current decreases because the capacitive current partly compensates the inductive current. The leakage field becomes smaller and the flux in the core increases and makes the voltage drop on the secondary side smaller.

If the transformer is loaded with a leading current, that is a current with a resulting reactive current, which is capacitive, this capacitive load supplies reactive power to the transformer. The magnetic flux in the core and the secondary voltage increase.

The reactive power of the magnetic energy of the leakage field is

$$Q = \omega \cdot L^2 = 2\pi f L I^2 = X I^2 \quad \text{VA(r)} \quad (36)$$

Here I is the load current flowing in either of the windings and X the reactance in ohm referred to same side of the transformer as I .

X can be calculated based on the geometric dimensions of the windings and the number of turns. For a simple two-winding arrangement the formula is:

$$X = 4\pi \cdot 10^{-7} (t_{12} + \frac{t_1 + t_2}{3}) \frac{L_1 + L_2}{h_w} k_R N^2 \cdot 2\pi f \quad \Omega \quad (37)$$

Dimensions in meter. N is the number of turns in the winding on the side to which X shall be referred. See Figure 6-11.

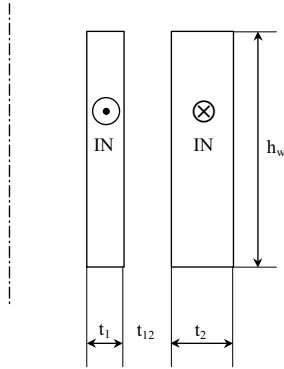


Figure 11-11

In the formula (37) L_1 and L_2 are the mean circumference for the inner and outer windings respectively. The formula is based on the assumption that the magnetic field lines goes vertically along the whole height h_w of the windings. This is in reality not the case. It can be seen from Figure 11-10 that some of the field lines towards the ends of the windings have an increasing horizontal or radial component. The German professor W. Rogowski made a careful study on how to compensate for this deviation from the assumption in the formula. The result of this study (published early in the last century) was a correction factor

$$k_R = 1 - \frac{(t_1 + t_{12} + t_2)}{\pi h_w} \left(1 - e^{-\frac{\pi h_w}{(t_1 + t_{12} + t_2)}} \right) \quad (38)$$

This factor has is known as the the Rogowski factor. In most practical cases its numerical value is within the range 0,95 – 0,99. It makes the length of the leakage field duct a little longer, h_w/k_R instead of h_w .

The formula for u_x expressed as a percentage of the rated voltage U_r is

$$u_x = 2 \left(t_{12} + \frac{t_1 + t_2}{3} \right) \frac{L_1 + L_2}{h_w} k_R \frac{(IN)}{e_{10}} \frac{f}{50} 10^{-2} \% \quad (39)$$

where e_{10} is the number of volts per turn in no load condition.

Corresponding hand formulas exist also for more complicated winding arrangements. The short-circuit reactance or short-circuit voltage calculated by means of these formulas comply very well with the measured values. However, for high currents an addition for the reactance in the lead assembly must be made.

11.10. ELECTROMAGNETIC FORCES

IEC 60076-5 Power transformers – Part 5: Ability to withstand short circuit identifies the requirements for transformers to sustain without damage the effects of overcurrents originated by external short circuits.

For three-phase transformers with two separate windings, the r.m.s. value of the symmetrical short-circuit current is calculated as:

$$I_{sc} = \frac{U}{\sqrt{3} \cdot (Z + Z_s)} \quad \text{kA} \quad (40)$$

Where Z_s is the short-circuit impedance of the system.

$$Z_s = \frac{U_s^2}{S} \quad \text{In ohms per phase (equivalent star connection)} \quad (41)$$

Where

U_s is the rated voltage of the system, in kilovolts (kV);

S is the short-circuit apparent power of the system, in megavoltamperes (MVA).

U and Z are defined as follows:

U is the rated voltage U_r of the winding under consideration, in kilovolts (kV)

Z is the short-circuit impedance of the transformer referred to the winding under consideration; it is calculated as follows:

$$Z = \frac{u_z \cdot U_r^2}{100 \cdot S_r} \quad \text{In ohms per phase (equivalent star connection)} \quad (42)$$

where

u_z is the measured short-circuit impedance at rated current and frequency at reference temperature, as a percentage;

S_r is the rated power of the transformer, in megavoltamperes (MVA).

The duration of the symmetrical short-circuit current must be limited to avoid excessive overheating. According to IEC 60076-5 the duration shall be 2s, unless otherwise agreed between purchaser and supplier. During this time the temperature in the windings shall not exceed certain values given in IEC 60076-5, when calculated by means of formulas given in the standard.

Another aspect of the short circuit topic is the mechanical forces in the windings due to overcurrents. Unlike temperatures that need some time to rise, the mechanical forces follow the current instantaneously. The first cycles of a short-circuit current are asymmetric with respect to the time axis. The degree of asymmetry depends on point of the sinusoidal voltage curve where the short-circuit occurs. The degree of asymmetry is a statistical variable with its maximum when the short-circuit occurs in the range where the voltage passes through zero and its minimum in the range where the voltage has its peak value. This will be demonstrated in the following.

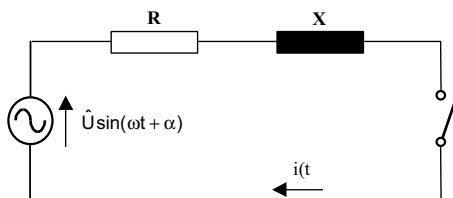


Figure 11-12

Consider the circuit in Figure 11-12. Assume that the switch makes at the instant $t = 0$, thus simulating a short-circuit. The current $i(t)$ is expressed by the following equation:

$$i(t) = \hat{I} \cdot (\sin(\omega t + \alpha - \varphi) - e^{-\frac{t}{\tau}} \cdot \sin(\alpha - \varphi)) \quad \text{A} \quad (43)$$

in which

$$\hat{I} = \frac{\hat{U}}{|Z|} \quad \text{A} \quad (44)$$

that is the peak value of the symmetrical, stationary short-circuit current

$$Z = R + j\omega L \quad [\Omega]$$

$$\alpha = \text{switching angle of the voltage } u(t) \text{ at the instant of the short circuit} \quad [\text{rad}]$$

$$\varphi = \text{phase angle of the circuit impedance } (= \arctg \omega L / R) \quad [\text{rad}]$$

$$\tau = L / R = \text{tg} \varphi / \omega \quad [\text{s}] \quad (\text{the time constant of the circuit})$$

$$\omega = 2 \cdot \pi \cdot f \quad [\text{s}^{-1}]$$

The current starts from zero and consists of two components:

- an alternating steady-state component of fundamental frequency,
- an unidirectional component decreasing exponentially with time.

The first peak value of the short-circuit current determines the maximum force that acts on the windings. The maximum value of this current depends on the X/R ratio and the switching angle α . It occurs in almost all cases when $\alpha = 0$ (or π).

In power systems $X \gg R$, which means that $\varphi \approx \pi/2$.

Equation (43) can then with reasonable approximation be written as:

$$i(t) = \hat{I} \cdot \left(\sin(\omega t - \frac{\pi}{2}) + e^{-\frac{R}{X}t} \right) \quad A \quad (45)$$

The first current peak closely corresponds to the time when $\omega t = \pi$.

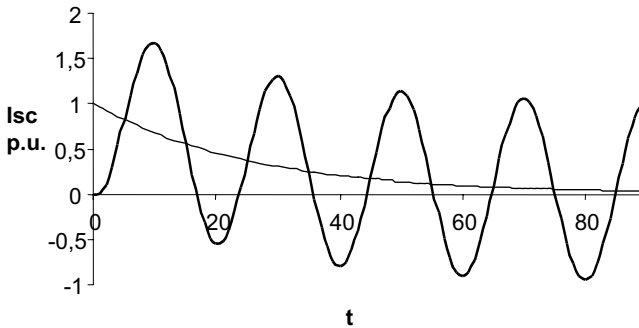


Figure 11-13

$$i = \hat{I} \cdot k = I_{sc} \cdot \sqrt{2} \cdot k = I_{sc \max} \quad A \quad (46)$$

where the asymmetry factor k is

$$k = 1 + e^{-\pi R/X} \quad (47)$$

Figure 11-13 shows an example on how the short-circuit current elapses. In this example $X/R = 8$, $k = 1,68$.

The peak factor is $k \cdot \sqrt{2}$ and its dependence of X/R is shown in Figure 11-14. The peak factor value in the example in Figure 11-13 is 2,38. The value of the first peak of the short circuit current is the r.m.s. value of the stationary short circuit current multiplied with the peak factor.

In a real case with a transformer installed in a network:

X = the sum of the network and the transformer reactance $[\Omega]$

R = the sum of the network and the transformer resistance $[\Omega]$

X/R and the peak factor increase with increasing transformer power rating.

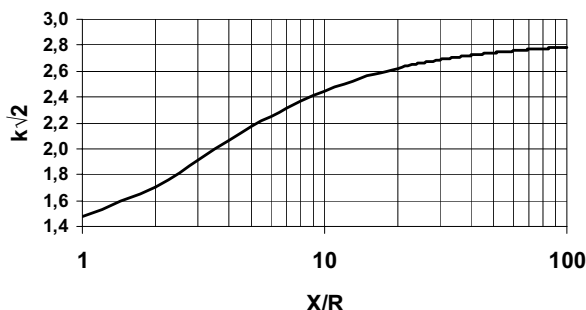


Figure 11-14

Mechanical forces in the windings

Current flows through the winding conductors, which are situated in the magnetic leakage field. The conductors are then subject to mechanical forces.

These forces are not static. They are pulsating. Each time the current passes through zero the forces are also zero. At normal load current the forces are small. They increase with the square of the current, so during the high overcurrents that arise if a short-circuit in the system occur, the forces must be given attention when designing the transformer. The short circuit current may amount to 10 – 20 times the rated current of the transformer, which means that the forces in the windings may be 100 – 400 times larger at a short circuit than in normal service. For transformers with extremely low short circuit impedance the figures might be still higher.

The forces cause large movements in the windings. These movements are invisible for the human eye. But rapid film recordings played in slow motion show the size of the movements and illustrate the violence of the forces.

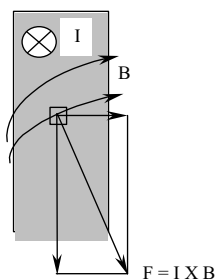
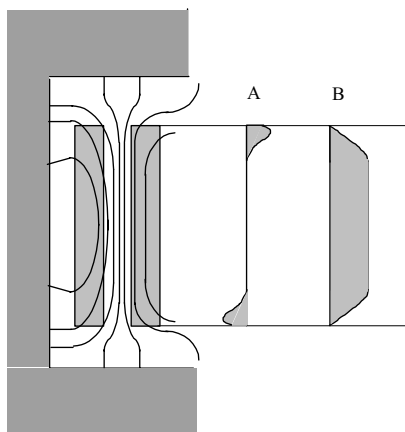


Figure 11-15

When considering the ability of a design to withstand it is usual to split the forces into radial and axial components as indicated in Figure 11-15, which shows an upper part of an outer winding. The radial force is directed outwards and causes a tensile force in the winding conductors. In the corresponding inner winding the radial component is directed inwards. That may cause buckling of the winding if it has not been made robust enough.

The axial forces are caused by the radial component of the magnetic field at the ends of the windings. These forces may lead to tilting of the conductors between the axial spacers in the winding. The force on each turn or disc adds together. The sum of the forces is balanced at the other end of the winding. The whole winding is subject to a strong axial pressure. See Figure 11-16.



A Axial current forces
B Resulting axial pressure

Figure 11-16

The ability to withstand tilting of the conductors depends on the diameter of the winding, the distance between the spacers around the circumference and the dimensions of the conductor.

In case of axial "openings" in the winding, that is one or more places along the height of the winding where there are no ampere-turns, there will be axial forces directed towards the yokes. The framework keeping the core and windings together must be designed to be able to withstand such forces.

A more comprehensive treatment of the short-circuit topic is given in the book "SHORT-CIRCUIT DUTY OF POWER TRANSFORMERS – THE ABB APPROACH" by Giorgio Bertagnolli, issued by ABB. The book is available from ABB at request.

11.11. TRANSFORMER SOUND

Transformers in service cause sound, which in the long run may seriously discomfort people in the environment.

Sound may be defined as any pressure variation in air (or other elastic media) that the human ear can detect. The pressure variations travel through the medium from the sound source to the listener's ears. The number of cyclic pressure variations per second is called the frequency of the sound, and is expressed in Herz (Hz). The frequency of a sound produces its own distinctive tone. A transformer 'hum' is low frequency, fundamentally 100 Hz or 200 Hz, while a whistle is high frequency, typically above 3 kHz. The normal range of hearing for a healthy young person extends from approximately 20 Hz to 20 kHz.

A further characteristic used to describe a sound is the amplitude of the pressure variations, which is expressed in Pascals (Pa). The weakest sound that a healthy human ear can detect is strongly dependent on the frequency; at 1 kHz it has amplitude of 20 μ Pa. The threshold of pain corresponds to a sound pressure of more than a million times higher. Therefore, to avoid the use of large numbers, the decibel scale (dB) is used.

The dB-scale is logarithmic and uses 20 μPa as the reference level, p_0 , which then corresponds to 0 dB. Sound pressure level L_p expressed in dB is defined in the following equation:

$$L_p = 10 \cdot \lg \frac{p^2}{p_0^2} \qquad \text{dB} \qquad (48)$$

where p is the sound pressure measured by a microphone. Sound pressure is a scalar quantity, which means it has magnitude only.

To provide a feeling of how a few well-known types of sound are situated on the dB-scale some values are listed below.

Source of sound	Sound pressure level in dB
Quiet living area	45
Normal conversation at 1 m distance	60
Medium factory noise	75
Factory maximum limit	85
City street with heavy traffic	95
Circle saw at 1 m distance	105

Comprehensive investigations are made to correlate human perception of 'loudness' at various frequencies and sound pressures. The curves in Figure 11-17 are results of such investigations. These curves will vary somewhat from one person to another, but they can be regarded as average curves for how young persons with healthy ears respond.

Each curve represents sound that is perceived as 'equally loud' across the whole frequency range. The lowest curve that goes through zero dB sound pressure at 1000 Hz represents the hearing threshold. The human ear is not able to hear anything below this curve. It appears that the ear is most sensitive in the frequency range between 3 and 4 kHz, where a sound pressure even below 20 μPa is audible.

For frequencies below 700 Hz the threshold curve ascends, which means that for the lower frequencies the sound pressure has to be increased to make the sound audible. The curve also rises at frequencies above 4 kHz.

The three upper curves go through 40, 70 and 100 dB at 1 kHz. A microphone responds quite differently to sound pressure. In order to imitate the response curves of the human ear filters are inserted in the measuring equipment. Three different filters are standardized, named A, B and C filters. They imitate the curves going through 40, 70 and 100 dB at 1 kHz respectively.

Measurement results made with one of the three filters inserted are denoted dB(A), dB(B) or dB(C).

Ear sensivity curves

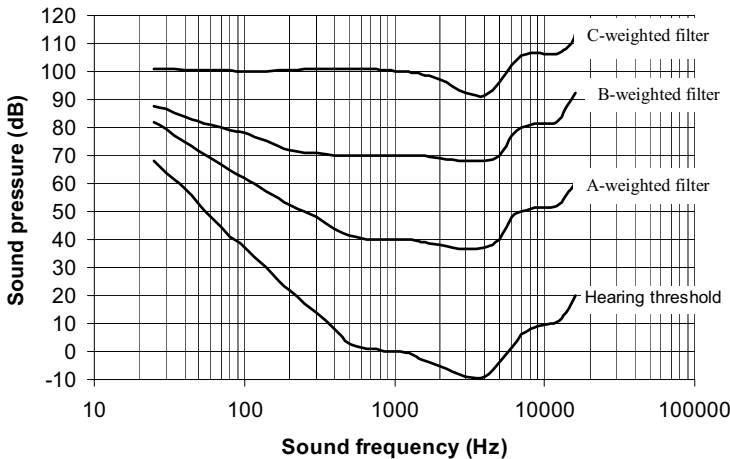


Figure 11-17

When measuring the sound pressure around a transformer, the A-filter is used because this corresponds to the sound pressure level that normally prevails.

The sound pressure caused by a transformer is measured in several points around the transformer at a distance of 0,3 meters from the outer vertical surface of the transformer. This measurement result is in itself of limited interest, because nobody normally is standing 0,3 meters from the transformer. More interesting is the sound pressure level at larger distance from the transformer where people may stay.

To be able to estimate the sound pressure at larger distance, the sound power level of the transformer must be determined. The term 'sound power' needs to be explained.

A sound source radiates power into the surrounding air resulting in a sound pressure field. Sound power is the cause. Sound pressure is the effect. The sound pressure, which is heard or measured with a microphone, is dependent on the distance from the source and the acoustic environment. So, the sound pressure at a certain distance from the source alone cannot quantify the strength of the source. It is necessary to determine the sound power of the source, which is independent of the environment and a unique descriptor of the strength of the sound source.

Sound power is the rate at which energy per unit time is radiated from the source. Its dimension is Watt. However, sound power L_w is normally also expressed in dB and logarithmic scale according to the following formula:

$$L_w = 10 \cdot \lg \frac{W}{W_0} \quad \text{db} \quad (49)$$

In this formula W_0 is an arbitrarily chosen reference value equal to 10^{-13} Watt, which corresponds to a quite weak sound source. This reference value is chosen without regard to the previously mentioned reference value for sound pressure.

The sound power of one of the strongest sound power sources of concern, a large jet motor, has a sound power of about 100 000 Watts. The total power range to deal with is then 10^{18} . Instead of working with such extremely high figures in acoustical subjects, the whole power range is covered by 180 dB.

Based on the measured sound pressure the sound power of the transformer in dB can be calculated according to formulas given in IEC 60076-10 Ed. 1.0.

In a large free field the sound pressure at larger distances from the transformer can be calculated. In practice there are often one or more walls or other items in the surroundings of the transformer that will reflect sound from the transformer and make a prediction of the sound pressure at various places in the neighbourhood difficult.

Sources of sound generation

The dominant generating source of transformer sound is magnetostriction. Magnetostriction is the change in dimensions which takes place in certain materials when they are subjected to a change in magnetic flux. In magnetic core steel the dimensional change is in the range of 10^{-7} to 10^{-5} meters per meter length at typical induction levels.

The effect does not depend on the sign of the flux, only on its magnitude and orientation relative to certain crystallographic axes of the material. Therefore, when excited by a sinusoidal flux, the fundamental frequency of the dimensional change will be twice the exciting frequency. The effect is highly non-linear, especially at high, near saturation, induction levels. The non-linearity results in a significant harmonic content in the vibration spectrum of the core.

In three-phase cores the change in dimension in each core limb does not occur simultaneously, which means that the whole core will be subject to pulsating distortions that also generate sound.

A DC bias in addition to the AC magnetization of the core may significantly increase the vibration amplitudes of the core and consequently the sound level. The DC bias may also cause a considerable difference in the positive and negative peaks of the flux density, which in turn makes the fundamental frequency of the sound equal to the frequency of the service voltage instead of twice this frequency.

There are a few means available to the transformer designer to reduce the sound generated from the core:

- Reduce the flux density in the core from the usual 1,7 – 1,85 Tesla down to 1,2 Tesla. This can be done either by increasing the core cross section or by increasing the number of turns in the windings. There is not much to gain in reduced sound level by going below 1,2 Tesla. Reduced flux density gives larger geometric dimensions, increased load losses and higher weight and manufacturing costs. The no load losses will decrease,
- Avoid combinations of core cross section and limb height that make natural frequencies of the core coincide with frequencies of the magnetic field,
- Making the framework that holds the core together heavier and stiffer,
- Inserting a pad of damping material between the active part of the transformer and the tank bottom.

Another source of sound from transformers is vibrations in the windings due to pulsating mechanical forces acting on the winding conductors. The windings are situated in the magnetic leakage field. The force acting on a winding conductor is proportional to the product of the current flowing in the conductor and the local flux density of the magnetic field where the conductor is situated.

At normal flux densities in the core, 1,7 T and above, the sound due to the core will overshadow the sound from the windings. But in cases where especially low sound levels are specified and the flux density in the core is low (down to 1,2 T) in order to fulfil the required sound level, the sound produced by the windings may give a noticeable contribution to the total sound level of the transformer.

Plane metal plates between stiffeners in the transformer tank may act like a membrane of a loudspeaker if any natural frequency of the plate coincides with a dominant frequency of the vibrations from the active part. The total sound level of the transformer may in such situations be considerably increased.

The measurement of sound from transformers may sometimes be disturbed by high background sound or sound from one or several other strong sound sources in the surroundings. To determine the sound power of the transformer in such situations sound intensity measurements are made. Sound intensity is the time-averaged product of the pressure and particle velocity of the medium in which the sound waves are propagating. Sound intensity is a vector quantity describing the magnitude and direction of the net flow of sound energy at a given position.

It is outside the scope of this chapter to explain the physics that form the basis for determining the sound power of a source by means of sound intensity measurements. We will just mention that two closely spaced microphones are used and that the measurement procedure and the determination of the results are described in IEC 60076-10.

Cooling fans create turbulent flows of air resulting in pressure fluctuations with a wide range of frequencies. The sound level is highly dependent on the speed of the fan wheel periphery.

The transmission of sound from the transformer to the surroundings can be reduced by installing sound-damping panels around the transformer or place the transformer inside a separate building.

Within large buildings transformer sound may propagate widely through structural parts of the building, like floors and walls. Inserting plates of suitable damping material between the transformer and its fundament can effectively reduce this.

The IEC transformer standards do not prescribe any permissible limits for transformer sound. They just describe how sound characteristics of transformers can be determined. Permissible limits are entirely subject to agreement between purchaser and supplier in each case.

The CENELEC transformer standard HD 428.1 S1:1992 has standardized limits for the sound level for the smallest distribution transformers.

12. THREE-PHASE TRANSFORMER CONNECTIONS

There are three basic ways to connect the phase windings of each side in three-phase transformers:

- Y-connection, also called star connection, where one end of the three phase windings are connected together in one point called the neutral point or the star point (Figure 12-1 to the left);
- D-connection, also called delta connection, where the three phase windings are connected in series and form a ring (triangle) (Figure 12-1 in the middle);
- Z-connection, also called interconnected star or zigzag connection (Figure 12-1 to the right).

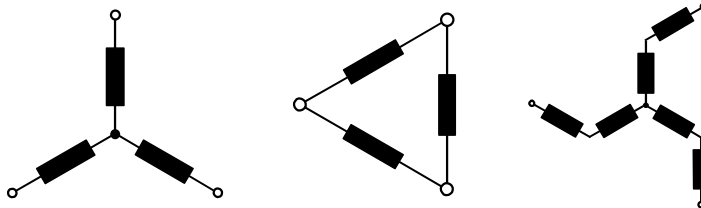


Figure 12-1

The primary, secondary and tertiary sides of a transformer may in principle be connected individually in any of the three ways indicated above. This offers several different combinations of connections in a transformer with different characteristics, which also may be influenced by the type of core. In this handbook the description will be limited to the most frequently used connection combinations.

The Y-connection is the natural choice of connection for the highest voltages and when the neutral is intended for loading. In any case a neutral bushing should be provided either for overvoltage protection purpose or for direct earthing. In the latter case the insulation level of the neutral may be made lower than in the phase end of the winding with economical benefit.

The Y-connected winding has also the benefit that tappings for turn ratio regulation can be provided at the neutral end where also a tap changer can be located. The tap changer will then operate at a low voltage level to earth, and the voltage difference between the phases is low as well. A cheaper tap changer can be selected compared to a tap changer located at a higher voltage level.

When Y-connection is used in one side of the transformer, one other side should preferably be delta connected, especially when the neutral of the Y-connected winding is intended to be loaded. The delta connected winding provides ampere-turn balance for the zero sequence current floating through the neutral and each phase of the Y-winding, which gives a reasonable zero sequence impedance. Without a D-connected winding the zero sequence current would create a zero sequence field in the core. If the core has 3 limbs, such a field will find its path from yoke to yoke through the tank wall and create excessive heating there. If the core has 5-limbs or is a shell type core, the field will find its path from yoke to yoke through the unwound side-limbs, and the zero sequence impedance will be extremely high. A consequence is that the current in case of an earth fault might become so small that the protecting relays do not react.

In a D-connected winding the current through each phase-winding is the line current divided by $\sqrt{3}$, while in a Y-connected winding the line current floating through each phase-winding is equal to the line current. On the other hand the D-connected winding requires $\sqrt{3}$ times as many turns as a Y-connected winding for the same voltage.

The D-connected winding is advantageous in large power transformers when the current is high and the voltage relatively low, like for example in the low voltage winding of generator step up transformers.

A D-connected winding enables triple harmonic currents to circulate inside the triangle formed by the three series-connected phase windings. Triple harmonics in the magnetisation current is required to avoid distortion of the magnetic flux in the core and in turn distortion from the sinusoidal shape of the induced voltage. The triple harmonic currents are equal in time-phase in all three phases, and these currents cannot float in a Y-connected winding unless the neutral of the winding is connected to a return path.

Lack of triple harmonics in the magnetising current may cause considerable distortion of the induced voltage when the core has 5 limbs or is a shell-type core. A D-connected winding in the transformer will remove this disturbance because the D-connected winding will provide the missing triple harmonic currents. Sometimes transformers are equipped with a tertiary D-connected winding which is not intended for loading but only for avoiding voltage distortion and reduction of zero sequence impedance. Such windings are called stabilising windings.

Distribution transformers for loading between phase and neutral have normally D-connected winding on the primary side. However, for the lowest power ratings the current in a D-connected winding might be very small and the required dimension of the winding conductor inconveniently small to handle in the factory. In such cases the high voltage winding may be Y-connected and the secondary winding zigzag-connected. Zero sequence currents floating in the two branches of the Z-connected winding will balance each other, and the zero sequence impedance seen from the secondary side is mainly determined by the magnetic leakage field between the two winding branches and is quite low.

By arranging the connection of a pair of windings in different ways it is possible to make a number of different degrees of voltage displacements between the sides of the transformer. Transformers that are connected in parallel on both sides require the same voltage displacement. The face of a watch has traditionally been used to describe the voltage displacement between the primary voltage and the secondary voltage and, when applicable, the displacement between the primary and the tertiary. One phase of the primary is pointing at twelve and the corresponding phase at the other side is pointing at any of the watch numbers.

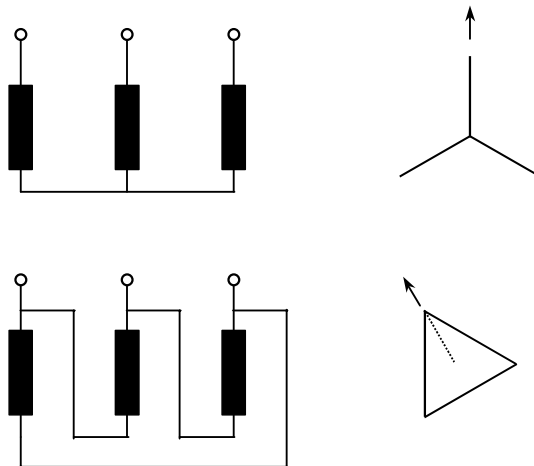


Figure 12-2

The frequently used combination Yd11 means for instance that there is 30 ° displacement between the voltages of the two sides as illustrated in Figure 12-2.

13. TRANSFORMER MATERIALS

13.1. CORE MATERIALS

Transformer cores are built from thin sheets of steel. These sheets are manufactured specifically for use in transformers.

Core steel has low carbon content $< 0.1\%$. Increased carbon content has a detrimental influence on the hysteresis losses as well as the ageing properties.

Core steel is alloyed with silicon (Si). Silicon increases the specific electrical resistance, which again reduces the eddy current losses in the core. Increased silicon content makes the core steel brittle; therefore the content is kept below 3%.

Today, only grain-oriented steel is used. By cold rolling the steel sheets, the magnetic domains in the steel sheet will tend to be oriented in the rolling direction.

One gets a material with very good loss properties in the rolling direction, and correspondingly poor properties in the transversal direction. The rolling process requires special equipment with very high surface pressure.

The grain oriented core steel is available in several grades. The different properties are obtained by the raw material composition, the degree of cold rolling and different finishing treatments, for example laser treatment. Laser treatment is a mechanical treatment which divides the magnetic domains into smaller domains with lower losses as the result.

To minimise eddy current losses, the sheets must be insulated from each other. Earlier it was common to use varnish or paper. Today the core steel is delivered ready insulated from the manufacturer. The insulation is an inorganic material compatible with transformer oil and is corrosion and temperature resistant. The insulating coating is very thin $< 4 \mu\text{m}$. A thin coating means a good core fill factor.

The core is built up from many layers of core steel sheets. Suppose the core limb was built from a solid iron bolt, the core would represent a short-circuited winding around itself, and the transformer would not work. The mutually insulated sheets prevent such a short-circuit.

Eddy current losses in the core steel are proportional to the square of the thickness. Therefore the steel sheets have to be thin in order to reduce the no load losses. Typical thickness is from 0,18 mm to 0,30 mm.

13.2. CONDUCTOR MATERIALS

From a technical and economical point of view there are two conductor materials that can be used, copper (Cu) or aluminium (Al).

The choice of conductor material depends mainly on price and availability. The supply and demand of copper and aluminium can vary quite significant on the world market, and thereby also price and availability of conductors from the manufacturers.

Some customers prescribe copper only, for different reasons, mainly conservatism.

The physical dimensions of a transformer with copper windings are normally smaller than that of a transformer with aluminium windings.

Conductor shapes are foil, round or rectangular wire.

The foil is not directly insulated. The round and rectangular wire is normally coated by varnish.

The use of varnish instead of paper improves the winding space factor due to smaller thickness, and reduces the winding to liquid temperature gradient (winding to air temperature gradient for dry-type transformers).

Rectangular wire can also be insulated by paper for thermal class 105 or with aramid for higher temperature classes.

Cold working of the conductor increases the mechanical strength and the ability to withstand short-circuit forces.

13.3. INSULATION MATERIALS

13.3.1. Solid insulation materials

13.3.1.1. General

A good insulation material must have the following properties:

1. High dielectric strength,
2. Good mechanical properties,
3. Long lifetime at operating temperature,
4. Easily workable.

Insulation material must withstand the operating temperatures that occur in the transformer during the lifetime of the transformer.

Insulation materials to be used in liquid-immersed transformers must be compatible to the liquid.

13.3.1.2. Cellulose materials

Mainly used in oil immersed transformers with thermal class 105.

Cellulose insulation is made of slow growing types of wood, having long fibres. Long fibres give long life-time, and high density gives high dielectric strength.

Cellulose products are compatible to mineral oil, and are easy to oil impregnate.

The impregnation is done under vacuum and elevated temperature, and the tiny cavities in the cellulose are filled with oil. Thereby the dielectric strength is further increased. In case the cavities were not filled with oil, these small air bubbles would cause partial discharges. Partial discharges may in the long term escalate to a dielectric break-down.

Contaminants represent weaknesses in the insulation that may lead to dielectric break-down.

Cellulose insulation is specified in IEC 60554-3 for paper, and IEC 60641-3 for board.

13.3.1.3. Wood

Laminated wood is used for different support purposes in liquid immersed transformers. The applicable IEC standard is 61061-1/2/3.

13.3.1.4. Porcelain

Porcelain is mainly used for bushings in oil-immersed transformers. In some cases also used as supports or spacers in dry type transformers.

13.3.1.5. Solid synthetic insulation materials

These materials are mainly used in dry type transformers or reactors having higher thermal classes 130, 155, 180, 220. These materials are more expensive than cellulose insulation.

Enamels are used as conductor insulation, and normally double coated. Several qualities for different applications are available. Reference is made to IEC 60317

Epoxy resins used in combination with fillers, for example glass fibre and quartz powder is used for insulation barriers and complete vacuum cast windings.

Polyesters can be used as insulation barriers, spacers and duct sticks. Reference is made to IEC 60893-3 and IEC 61212-3

Aramid fibre are used to manufacture insulation paper or board sheets in different thicknesses. The material surface may be smooth or porous. The porous type can to a certain extent be oil impregnated. The material has very good thermal properties, thermal class 220.

Aramid insulation is specified in IEC 60819-3 for paper, and IEC 60629-1 for board.

13.3.2. Fluids

13.3.2.1. General

The fluid in a transformer has several functions; the two most important are certainly insulation and cooling. Another function is to carry information about the condition of the active part inside the transformer.

Several requirements have to be fulfilled;

Chemical	Electrical
Oxidation stability	Breakdown voltage AC
Oxidation inhibitor content Inhibitor is recommended	Breakdown voltage, impulse
Corrosive sulphur	Dissipation factor
Water content	Streaming charging
Neutralization value	
Physical	Additional
Viscosity	Low particle content
Appearance	Compatibility with other transformer materials
Density	Gassing properties
Pour point	Aromatic structure
Surface tension	Poly-aromatic structure
Flash point	Solubility properties

13.3.2.2. Mineral oil

Important properties of mineral oil are specified in IEC 60296.

Flash point 145 °C, density 0,88 kg/dm³, relative permittivity 2,2.

Mineral oil is the most common liquid used. Mineral oil is normally the reference to which all other liquids are compared.

Mineral oil offers in most cases the best compromise between cost and technical properties, and compatibility with other transformer materials is also very good.

Inhibitors retards the ageing process of the oil.

13.3.3. Other fluids

These fluids are reserved for special applications, and are typically 5-6 times more expensive than mineral oil.

The main motivation for using these fluids is improved fire safety and environmental impact.

Further these fluids are applicable for operation at elevated temperatures, however have limited capabilities in extremely cold climates.

13.3.3.1. Dimethyl Silicone

Important properties of silicone fluid are specified in IEC 60836

Flash point 310 °C, density 0,96 kg/dm³, relative permittivity 2,7.

Silicone fluid has lower dielectric and cooling properties compared to mineral oil.

When it ignites it is self-quenching because it creates a layer of oxide. However, it is not self-quenching related to arcing and electrical failures.

Silicone fluid is not used in on-load tap changers a.o. due to its poor lubrication properties.

13.3.3.2. Synthetic Ester

Important properties of synthetic ester are specified in IEC 61099

Flash point 275 °C, density 0,97 kg/dm³, relative permittivity 3,2.

13.3.3.3. Synthetic Hydrocarbon

Important properties of synthetic hydrocarbon are specified in IEC 60867

Flash point 230 °C, density 0,83 kg/dm³, relative permittivity 2,1.

13.3.3.4. Agricultural Ester

No applicable IEC specification.

Flash point 330 °C, density 0,91 kg/dm³, relative permittivity 3,2.

This is good compromise between fire safety and environmental friendliness.

BIOTEMP is an ABB developed and patented agricultural ester, based on sunflower oil, see also www.abb.com/transformers for additional information.

14. TESTING OF TRANSFORMERS

The information given below is an extract from IEC 60076-1 (1993-03) Clause 10. Testing of dry-type transformers is described in IEC 60726 (1982) for further information. *Copyright © IEC, Geneva, Switzerland. www.iec.ch

ABB has issued a comprehensive book on this subject, see section 17.2 page 200. This book describes testing both according to IEC and ANSI/IEEE standards.

14.1. GENERAL REQUIREMENTS

- Tests shall be made at any ambient temperature between 10 °C and 40 °C, and with cooling water if required at any temperature not exceeding 25 °C,
- Tests shall be made at the manufacturer's works, unless otherwise agreed between the manufacturer and the purchaser,
- All external components and fittings that are likely to affect the performance of the transformer during the test shall be in place,
- Tapped windings shall be connected on their principal tapping, unless the relevant test clause requires otherwise or unless the manufacturer and the purchaser agree otherwise,
- The test basis for all characteristics other than insulation is the rated condition, unless the test clause states otherwise,
- All measuring systems used for the tests shall have approved, traceable accuracy and be subject to periodic calibration, according to the rules of 7.6 of ISO 9001.

NOTE: Specific requirements regarding accuracy and verification of measuring systems are under consideration within CENELEC.

Where it is required that test results are to be corrected to a reference temperature, this shall be; for oil-immersed transformers: 75 °C, and for dry-type transformers: according to the requirements in IEC 60726.

14.2. ROUTINE TESTS

- Measurement of winding resistance (IEC 60076-1 10.2),
- Measurement of voltage ratio and check of phase displacement (IEC 60076-1 10.3),
- Measurement of short-circuit impedance and load loss (IEC 60076-1 10.4),
- Measurement of no-load loss and current (IEC 60076-1 10.5),
- Dielectric routine tests (IEC 60076-3),
- Tests on on-load tap-changers, where appropriate (IEC 60076-1 10.8).

PD test will be a routine test in the new IEC standard for dry-type transformers, now in process.

14.3. TYPE TESTS

- Temperature-rise test (IEC 60076-2),
- Dielectric type tests (IEC 60076-3).

14.4. SPECIAL TESTS

- Dielectric special tests (IEC 60076-3),
- Determination of capacitances windings-to-earth, and between windings,
- Determination of transient voltage transfer characteristics,
- Zero-sequence impedance(s) on three-phase transformers (IEC 60076-1 10.7),
- Short-circuit withstand test (IEC 60076-5),
- Determination of sound levels (IEC 60076-10),
- Measurement of the harmonics of the no-load current (IEC 60076-1 10.6),
- Measurement of the power taken by the fan and oil pump motors,
- Measurement of insulation resistance to earth of the windings, and/or measurement of dissipation factor ($\tan \delta$) of the insulation system capacitances. (These are reference values for comparison with later measurement in the field. No limitations for the values are given here.).

NOTE: If tests other than those listed above are specified in the contract, such test methods are subject to agreement

15. OVERVOLTAGES AND OVERVOLTAGE LIMITATION

Transformers may in service be exposed to voltages in excess of the normal operating voltage. These overvoltages are classified with regard to their duration in two main groups:

- Temporary overvoltages (TOV)
- Transient overvoltages

A temporary overvoltage is a power frequency voltage of relatively long duration, ranging from less than one second up to several hours.

A transient overvoltage is a short-duration overvoltage ranging from nanoseconds up to a few milliseconds. The front time may vary from nanoseconds up to a few milliseconds. Transient overvoltages may be oscillatory or non-oscillatory. They are usually unidirectional.

A transformer may also be exposed to combinations of temporary and transient overvoltages. Transient overvoltages may be immediately followed by temporary overvoltages.

Overvoltages are also classified in two main groups with regard to their origin:

- Overvoltages caused by atmospheric phenomena,
- Overvoltages generated within the power system.

Overvoltages caused by atmospheric phenomena.

These are transient overvoltages mostly due to lightning strokes to earth near overhead lines connected to the transformer, although lightning can in some cases also directly strike the line or even the transformer.

The peak value of the voltage depends on the lightning current, which is a statistical variable. Lightning currents of more than 100 kA have been registered. According to measurements on overhead lines the 50% probability peak value of the lightning current is in the range 10 – 20 kA in most investigations. The distance between the transformer and the spot of the lightning stroke has an influence on the front time of the surge that strikes the transformer, the shorter distance from the transformer the shorter front time.

Overvoltages generated within the power system.

This group contains both temporary and transient overvoltages due to sudden changes in the service conditions in the power system. Such changes are caused by switching operations or failures.

Temporary overvoltages are caused by earth faults, load rejections and low frequency resonance phenomena.

Transient overvoltages occur when equipment is connected to or disconnected from the system. They can also occur when external insulation flashes over. When switching reactive loads, transient voltages may amount to 6 – 7 p.u. due to multiple transient current interruptions in the circuit breaker with front times down to fractions of a microsecond.

Transformer ability to withstand overvoltages.

Transformers are designed to withstand certain dielectric tests before delivery from the factory. These tests shall verify that the transformer has a high probability of reliable operation.

The tests are specified in international or national standards. Service experience confirms that transformers, which have passed such tests, are reliable with very few exceptions.

But an additional condition for the high service reliability is that adequate overvoltage limitation is provided, because the transformer may in service also be exposed to more severe overvoltages than those applied in the delivery test.

In power system planning the importance of considering all types of overvoltages that the equipment may be exposed to should be emphasized. To be able to do this in an appropriate way, physical understanding of the origin of the various types of overvoltages is necessary.

The magnitude of several kinds of overvoltages is a statistical variable. The ability of the insulation to withstand overvoltages is also a statistical variable. It is a task for the system planner, who has the overview and the knowledge about the system, to choose precautions to prevent overvoltage damage on the equipment. This includes balancing the costs for such precautions against the statistical risk for failures and their economical consequences. Suppliers of the equipment may make guarantee reservations in cases where precautions regarding limitations of overvoltages are missing or obviously insufficient.

15.1. LIMITATION OF TEMPORARY OVERVOLTAGES

15.1.1. Overvoltages due to earth-fault

A phase-to-earth fault may result in phase-to-earth overvoltages affecting the two other phases. The system parameters determine such overvoltages, which can only be controlled by affecting these parameters while designing the system.

It should be recognised that surge arresters are normally not suitable to limit temporary overvoltages due to the duration of such overvoltages and the limited thermal capability of the surge arresters.

The overvoltage on the sound phases during an earth-fault is usually expressed by means of the earth fault factor. In the International Electrotechnical Vocabulary (IEV) issued by IEC the earth fault factor is given the following definition:

The earth fault factor is at a given location of a three-phase system, and for a given system configuration, the ratio of the highest r.m.s. phase-to-earth power frequency voltage on a healthy phase during a fault to earth affecting one or more phases at any point on the system to the r.m.s. phase-to-earth power frequency voltage, which would be obtained at the given location in absence of any such fault. [IEV 604-03-06]

During a single-phase earth-fault the system will be in an non-symmetrical condition and the earth-fault factor is calculated by means of symmetrical components. The complex impedances of the system seen from the location of the earth-fault are:

$Z_1 = R_1 + j X_1$: resistance and reactance of the positive sequence system

$Z_2 = R_2 + j X_2$: resistance and reactance of the negative sequence system

$Z_0 = R_0 + j X_0$: resistance and reactance of the zero sequence system

If the following assumptions are made:

$Z_1 \approx Z_2$, $R_1 \ll X_1$ and that the fault resistance $R = 0$,

a diagram, that illustrates how the earth-fault factor at the location of the fault varies with X_0/X_1 for different values of R_0/X_1 , can be drawn.

The diagram is shown in Figure 15-1.

The curves show the earth-fault factor at the location of the fault. In extended resonant earthed networks the earth-fault factor may be higher at other locations than the fault.

X is positive for inductive reactances and negative for capacitive reactances. The earth fault current is inductive for $X_1/X_0 > -2$ and capacitive for $X_1/X_0 < -2$. When

$X_0/X_1 = -2$ the system is in a resonance condition.

It can be seen that unfavourable combinations of the parameters X_1 , X_0 and R_0 will give very high overvoltages that may destroy the surge arresters and the insulation of transformers and other equipment. The high overvoltages can only be reduced by changing these three parameters.

When for example X_0 and R_0 both are zero, the earth-fault factor is 0,866, which means that the highest voltage to earth on one of the healthy phases is 0,866 times the normal voltage between phase and neutral. In this case the two healthy phases are each operating at half the line-to-line voltage with opposite polarity referred to earth.

For small positive values of X_0/X_1 , the earth-fault factor increases with increasing R_0 . For high values of R_0 the earth-fault factor approaches $\sqrt{3}$.

At high positive or negative values of X_0/X_1 the earth-fault factor approaches also $\sqrt{3}$ nearly independent of R_0 .

At low negative values of X_0/X_1 the earth-fault factor may become very high, but it can be reduced by selecting a high R_0 .

A low earth-fault factor has the advantage that it allows a low protection level of the surge arresters. Thus the safety margin between the insulation level (BIL) of the transformer and the protection level of the surge arresters can be kept relatively high, depending on the duration of the fault, which is the other main parameter that influences the choice of the surge arresters.

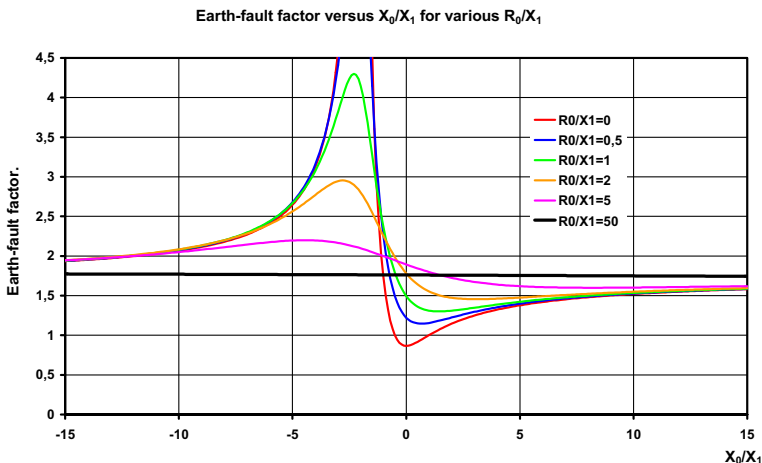


Figure 15-1

The duration of the overvoltage corresponds to the duration of the fault and will remain until fault clearing. In systems without earth-fault clearing the duration may be several hours. This will imply surge arresters with higher protection level and lower safety margin regarding transient overvoltages.

In insulation co-ordination knowledge about the earth-fault factor at various places in the network, in different loading conditions and system configurations is of vital importance. A thorough system analysis is necessary.

15.1.2. Load rejection overvoltages

A full load rejection in moderately extended systems can give rise to phase-to-earth and phase-to-phase overvoltages with amplitude usually below 1,2 p.u. The overvoltage duration depends on the operation of the voltage-control equipment and may be up to several minutes. Special precautions to protect distribution transformers against overvoltages due to load rejection are normally not needed

15.1.3. Overvoltages due to ferroresonance

Ferroresonance may occur in circuits with inductive elements having non-linear magnetizing characteristics (reactors with iron core or transformers in no load or low load condition) and large capacitive elements (lines, cables and capacitors).

The frequency of these overvoltages is equal or close to the frequency of the power system, that is a low frequency.

Overvoltages due to ferroresonance may occur in certain fault situations like:

- malfunction of a circuitbreaker if it fails to break or close in one or two phases during switching operation,
- one or two phase conductors are ruptured during earth fault, short-circuit or due to mechanical stresses,
- fuses are blown in one or two phases.

Transformer failures caused by overvoltages due to ferroresonance do not seem to occur frequently, but the risk is not negligible when the capacitive current of the system is of the same size as the magnetizing current of the transformer. Providing automatic and quick disconnection of the transformer in case the supply should fail in one or two phases will limit the duration of the overvoltage and system instability and reduce the extent and probability of material damage.

15.2. LIMITATION OF TRANSIENT OVERVOLTAGES

The ability of a transformer to withstand transient overvoltages is characterised by its basic impulse level (BIL), which corresponds to the peak value of the standard test voltage impulse. This is an aperiodic voltage impulse with a front time of 1,2 μ s and a time from the beginning to half the peak value of 50 μ s. The BIL of a transformer is also called the insulation level of the transformer.

Transformers connected to overhead lines should be protected against transient overvoltages caused by lightning to secure high service reliability. Limitation of the overvoltage can be achieved by means of:

- non-linear resistor-type surge arresters with series gaps,
- metal-oxide surge arresters without gaps,
- spark gaps, that is an open air gap between two terminals.

These devices are in most cases connected between each phase terminal of the transformer and earth. If the neutral point of y- and z-connected windings is isolated or earthed through a high inductance or resistance, a three-phase impulse wave will be reflected with the same polarity and an increased peak value at the neutral point. For this reason the neutral point should also be provided with overvoltage protection.

The protection level of surge arresters is normally selected lower than the insulation level of the transformer in order to provide a certain safety margin. A protection level around 70% of the insulation level of the transformer is frequently aimed at for the surge arresters at the phase terminals. However, when using non-linear resistor-type surge arresters with series gaps, it must be checked that the arc in the series gaps will extinguish with sufficient safety margin when the transient overvoltage has passed away but with a sustained temporary overvoltage corresponding to the actual earth-fault factor.

The protection level of a surge arrester in the neutral point is normally chosen to be around 3/4 of the protection level of the surge arresters at the phase terminals.

To provide optimum protection the distance between the surge arresters and the terminals of the transformer to be protected should be as short as possible. The same goes for the distance from the earthing terminal of the arresters to the earth. In cases where short connections to the surge arresters are difficult to achieve for practical reasons, selection of a higher insulation level for the transformer should be considered.

Windings for rated voltages below 1000 V should also be protected in the same way when they are connected to overhead lines.

In general metal-oxide surge arresters without gaps offers the possibility to select a lower protection level than the non-linear resistor-type surge arresters with series gaps. Thus an increased safety margin between the insulation level of the transformer and the protection level of the surge arrester can be achieved.

It must be kept in mind that metal-oxide surge arresters also will be continuously exposed to the normal service voltage, and in addition, to all kinds of smaller and larger temporary and transient overvoltages, contrary to the non-linear resistor-type surge arresters with series gaps. In the latter type the resistor is exposed only during transient overvoltages that are high enough to ignite the series gaps.

Spark gaps have been widely used in the past especially at moderate rated voltages, but they have several disadvantages:

- unpredictable sparkover voltage,
- long and unpredictable time delay to breakdown,
- strong dependence on wave shape,
- dependence on voltage polarity,
- dependence on ambient conditions,
- risk of creating an evolving fault,
- imposing a short-circuit condition on the network,
- creating chopped waves.

Due to the superior properties of metal-oxide arresters they are becoming increasingly preferred over spark gaps in modern systems. But in locations with frequent lightning storms with high lightning currents spark gaps can be useful in combination with metal-oxide arresters. Spark gaps installed at one or two poles of the overhead line away from the transformer will lead the highest current surges to earth before they reach the metal-oxide arresters at the transformer terminals. In this way the spark gaps will reduce the ageing of the arresters. A high number of high lightning current surges will contribute to ageing of the arresters.

Transformers installed in locations where they are not exposed to lightning overvoltages will still be exposed to transient overvoltages caused by switching operations.

The service experience regarding oil-immersed transformers in such locations indicates that they seem to withstand such overvoltages without being protected by surge arresters.

15.3. SPECIAL PRECAUTIONS FOR DRY-TYPE TRANSFORMERS

In locations which are not exposed to lightning overvoltages, a higher failure rate on dry-type transformers than on oil-immersed transformers has been observed on dry-type transformers when adequate protection against transient overvoltages is missing. Failures have also occurred on dry-type transformers in spite of being protected by surge arresters.

The explanation is that extremely steep overvoltages occur during prestrikes and reignitions in the circuit breaker after the current has been chopped outside its natural passage through zero. The internal overvoltages within a winding are not only depending on the peak value of the voltage arising at the terminals, but also on the steepness of the voltage change at the terminals. Thus a voltage with a peak value below the protection level of the arrester may damage the transformer if the change in terminal voltage takes place in just a fraction of a microsecond. Oil-immersed transformers seem to be more robust against such stresses compared to dry-type transformers. For the latter type the need for adequate protection should be recognised.

Attention should be paid to the physical fact that the transient overvoltages that arise when breaking inductive currents like the magnetizing current of a transformer is independent of the system voltage. They increase with the magnetic energy stored in the transformer core at the moment of current chopping. In other words, these transient overvoltages increase with the size of the transformer, and are most severe for transformers for low system voltages due to their lower insulation level. Because of the statistical nature of the size of the transient voltages, transformers that are more frequently disconnected and energized are, if not adequately protected, more prone to fail than transformers that are continuously energized for several years between each disconnection.

To summarise this, the need to protect for example a 2000 kVA, 10 kV transformer that is frequently switched in and out is higher than to protect a 100 kVA, 20 kV transformer that is energized continuously for long periods without being disconnected.

Capacitors between transformer terminals and earth will reduce the number of reignitions in the circuit breaker, or even in some cases eliminate them. The capacitors will also reduce the front steepness of the incoming wave during energizing and reduce the risk of transformer failure

Switching of capacitor banks for phase compensation has sometimes caused failures in dry-type transformers. The use of circuit breaker with opening and closing resistors has considerably reduced such failures.

Another possibility is using circuit breaker with point-on-wave control, which close and open at the most favourable time to minimize the transients.

15.3.1. Internal overvoltages caused by high frequency oscillations

Switching operations are always followed by high frequency oscillations in the kHz and MHz range, with slow or rapid damping. If the damping is slow and the dominating frequency of the oscillations coincide with one of the resonance frequencies of the transformer, high local turn-to-turn voltage stresses within the winding arise and may cause a failure.

Opening and closing resistors on the circuit breaker will effectively damp such oscillations.

Alternatively the dominating frequency of the oscillations could be changed (lowered) by installing additional capacitance. When choosing this solution, the resonance characteristics of the transformer should be known and a careful study of the power system should be made.

15.4. TRANSFERRED OVERVOLTAGES IN TRANSFORMERS

For high frequencies (kHz) the voltage ratio might be quite different from the turn ratio, with risk of high voltage transferred from one side to another that may damage the other winding if the transferred voltage is magnified by resonance effects.

Transferred voltages in transformers can have the following modes:

- electromagnetic transfer,
- electrostatic or capacitive transfer,
- oscillatory transfer through natural oscillations of the primary and/or the secondary circuits of the transformer. The earth capacitances and the self-inductances of the windings form the oscillation circuits.

Transferred overvoltages can be critical if:

- the secondary winding is not connected to the network,
- the secondary winding has a low rated voltage compared to the rated voltage of the high voltage winding,
- the winding is the tertiary of a three-winding transformer.

Surge arresters between phase terminals as well as between phases might be justified. Annex E of IEC 60071-2 goes a little more in detail on this subject.

In any case, the minimum precaution is that a secondary or tertiary winding that is not connected to the network, should be earthed in one point, one corner of delta windings and preferably the neutral of star windings.

16. MISCELLANEOUS

16.1. CERTIFICATION/APPROVAL/LABELLING

The CE mark (Communauté Européenne, European Conformity) based on European Directives assists the free distribution of goods on the European market. It is directed to the national standards supervising bodies. When the manufacturer applies the CE mark, this states that the legal requirements for the commercial product have been met. The CE mark is not a quality designation, a safety designation or a designation of conformity to a standard.

The following three European Union Directives may be applicable to transformer installations:

The *Machine Directive* covers most types of machines, with the exception of certain special types that are specifically excluded. The power supply companies and the manufacturers in Europe (EURELECTRIC/UNIPED and CAPIEL) have always been of the unanimous opinion that high-voltage equipment is not subject to the Machine Directive. The European Commission now shares this view. It should also be noted that motors, by definition, are not covered by the Machine Directive.

The *EMC Directive* is intended for application to almost all electrical equipment. However, fixed installations (which are assembled at the site of operation) have to meet the EMC protection requirements but they do not require a declaration of conformity, a CE mark nor an approval by any competent authority. This also applies to all primary and secondary devices in these installations (as components with no direct function).

The *Low Voltage Directive (LVD)* is applicable to independent low-voltage equipment which is also used in transformers and installations, such as control circuits, protection relays, measuring and metering devices, terminal strips, etc. This equipment must conform to the LVD and have a CE mark when purchased on the open market.

However, if control, measuring, protection and regulating equipment is a fixed component of high-voltage substations and/or transformers, it is not covered by the Low-Voltage Directive, because by definition (as per IEC 60050-441) they are considered to be high-voltage products.

In conclusion it is noted that high-voltage equipment and installations, including secondary installations, do not require a CE mark. However, they are subject to the relevant standards and regulations.

In North America transformers may be delivered with Underwriters Laboratories Inc. (UL) and CSA recognition/labels.

16.2. **DECLARATION OF CONFORMITY**

A Declaration of Conformity (DoC) according to *EN 45014 General criteria for supplier's declaration of conformity* will be issued if the customer requests it.

In some cases the designation Certificate of Conformity or similar is in use.

DoC will at minimum identify the supplier, the product, the conformity statement, the normative documents (with edition/date of issue) the transformer is in conformity with and possible additional information. The DoC shall denote place and date of issue as well as name, function and signature of the authorized person(s) acting on behalf of the supplier, see example:

Declaration of conformity

No.

Supplier:

Address:

Product:

The product described above is in conformity with:

Document No.	Title	Edition/Date of issue
.....		
.....		
.....		

Additional information

.....

.....

.....

Place and date of issue

.....

Name, functionSignature

16.3. **IP-CLASSIFICATION**

16.3.1. **General**

IP classification describes to what extent electrical equipment, in this regard the transformer terminals as well as accessories, are protected against touching and external influence such as dust, pollution, moisture etc.

Reference is made to IEC 60529 for a detailed description on this subject. *Copyright © IEC, Geneva, Switzerland. www.iec.ch

Explanation of numerals : IP23

The first characteristic numeral (2) describes the protection against solid foreign objects of 12.5 mm diameter and greater.

The second characteristic numeral (3) describes the protection against spraying water.

16.3.2. Degrees of protection against solid objects

Description	Definition	First Characteristic Numeral
Non-protected		0
Protected against solid foreign objects of 50mm diameter and greater	The object probe, sphere of 50 mm diameter shall not fully penetrate	1
Protected against solid foreign objects of 12.5mm diameter and greater	The object probe, sphere of 12.5 mm diameter shall not fully penetrate	2
Protected against solid foreign objects of 2.5mm diameter and greater	The object probe, sphere of 2.5 mm diameter shall not penetrate at all	3
Protected against solid foreign objects of 1.0mm diameter and greater	The object probe, sphere of 1.0 mm diameter shall not penetrate	4
Dust protected	Ingress of dust is not totally prevented, but dust shall not penetrate in a quantity to interfere with satisfactory operation of the apparatus or to impair safety	5
Dust tight	No ingress of dust	6

16.3.3. Degrees of protection against water

Description	Definition	Second characteristic numeral
No protection		0
Protected against vertically falling water drops	Vertically falling water drops shall have no harmful effects	1
Protected against vertically falling water drops when enclosure tilted up to 15 degrees	Vertically falling water drops shall have no harmful effects when the enclosure is tilted at any angle up to 15 degrees on either side of the vertical axis	2
Protected against spraying water	Water sprayed at an angle up to 60 degreed on either side of the vertical axis shall have no harmful effects	3
Protected against splashing water	Water splashed against the enclosure from any direction shall have no harmful effects	4
Protected against water jets	Water projected in jets against the enclosure from any direction shall have no harmful effects	5
Protected against powerful water jets	Water projected in powerful water jets against the enclosure from any direction shall have no harmful effects	6

16.3.4. Comparison to NEMA ratings

IEC 60529 does not specify degrees of protection against mechanical damage of equipment, risk of explosions, or conditions such as moisture (produced for example by condensation), corrosive vapors, fungus, or vermin. The NEMA Standard for Enclosures for Electrical Equipment does test for environmental conditions such as corrosion, rusty, icing, oil, and coolants. For this reason, and because the test and evaluations for other characteristics are not identical, the IEC Enclosure Classification Designations cannot be exactly equated with the enclosure Type numbers in the NEMA Standard.

The following table provides an equivalent conversion from the enclosure Type numbers in NEMA Standard to the IEC Enclosure Classification Designations. The NEMA enclosure type numbers meet or exceed the test requirements for the associated IEC Classification; for this reason the table cannot be used to convert from IEC Classifications to NEMA enclosure Type numbers.

NEMA Enclosure Type Number	IEC Enclosure Classification Designation
1	IP10
2	IP11
3	IP54
3R	IP14
3S	IP54
4 and 4X	IP56
5	IP52
6 AND 6P	IP67
12 AND 12K	IP52
13	IP54

16.4. TERMINAL DESIGNATION, IDENTIFYING TERMINALS

Unless the customer specifies terminal marking otherwise, ABB suggests that the terminals shall be marked according to IEC 60616 TR or ANSI/IEEE C57.12.70-1978™.

IEC standards specifies that external terminals shall be marked with reference numbers, which shall precede a reference letter (1U,1V,1W). The high-voltage terminals shall be marked with the reference number 1, and the other terminals with 2,3,4 ... in descending sequence of their rated voltage. The letter N shall mark the neutral terminals on transformers having star or zigzag connection.

ANSI/IEEE standards specifies that external terminals shall be marked with capital letter, which shall precede a reference subscript number (H_1, H_2, H_3). The highest voltage terminals shall be marked with capital letter H, the other voltage with X, Y and Z in order of decreasing voltage. The subscript number 0 shall mark the neutral terminals on transformers having star or zigzag connection.

16.4.1. Single phase transformer

According to IEC 60616 TR, the two terminals at the high-voltage side shall be marked 1.1 and 1.2 and the two terminals at the low-voltage side should be marked 2.1 and 2.2.

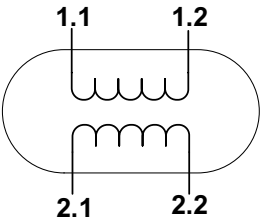


Figure 16-1

According to ANSI/IEEE C57.12.70-1978™, the two terminals at the high-voltage side shall be marked H_1 and H_2 and the two terminals at the low-voltage side shall be marked X_1 and X_2 .

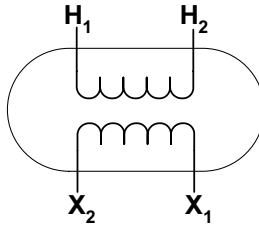


Figure 16-2

When Single-Phase transformers are used in a three-phase system, they are connected in Three-Phase Banks. In figure Figure 16-3 is an example with three Single-Phase transformers connected Δ -Y used in Three-Phase Banks with 30° angular displacements.

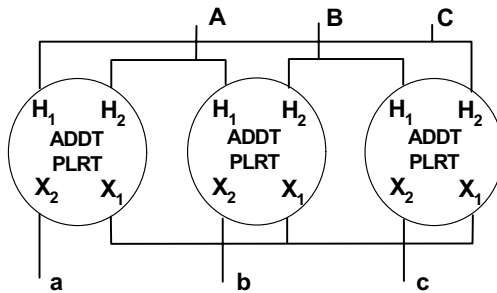


Figure 16-3

For more information about how to use single-phase transformers in three-phase banks see ANSI/IEEE C57.12.70-1978™.

16.4.2. Three phase transformer

According to IEC 60616 TR, the terminals shall be located and marked from left to right in following sequence, at the high-voltage 1W, 1V, 1U, 1N, and at the low-voltage 2W, 2V, 2U, 2N both seen from the low-voltage side. (1N and 2N are the neutral terminals.)

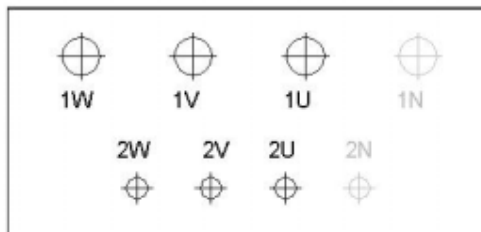


Figure 16-4

According to ANSI/IEEE C57.12.70-1978™, the terminals shall be located and marked from left to right in following sequence, at the high-voltage H_0 , H_1 , H_2 , H_3 , and at the low-voltage X_0 , X_1 , X_2 , X_3 side both seen from the low-voltage side. (H_0 and X_0 are the neutral terminals.)

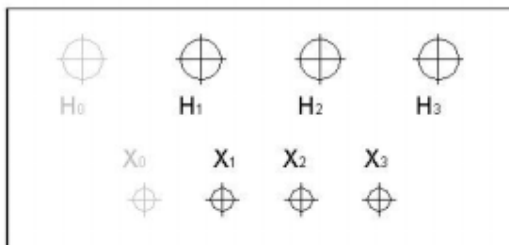


Figure 16-5

16.5. RATING PLATE

Transformers shall be provided with a rating plate of weatherproof material in visible position. All entries on the plate shall be indelibly marked.

Please see standard IEC 60076-1 for complete description to the rating plate information for the different types of transformers. *Copyright © IEC, Geneva, Switzerland. www.iec.ch

Below is the minimum information to be given for each transformer:

- Kind of transformer,
- Number of the applied standard,
- Manufacturer's name,
- Manufacturer's serial number,
- Year of manufacture,
- Number of phases,
- Rated power (kVA or MVA),
- Rated frequency (Hz),
- Basic insulation levels,
- Rated voltage and tapping range (V or kV),
- Rated currents (A or kA),
- Connection symbol,
- Short-circuit impedance (%),
- Type of cooling,
- Total mass,
- Mass of insulating oil.
- For dry-type transformers:
 - Temperature class,
 - Climatic class,
 - Environmental class,
 - Fire behaviour class,
 - Degree of protection (IP class).

Below is an example of the default ABB rating plate for transformers of type SDT and dry-type transformers. When customer specification requires additional information, this will be added as an extra plate or a different rating plate.

So far no standardised power transformer rating plates are defined by ABB.



Serial number				Prod. year			
- Phase Distribution Transformer							
Rated Power		kVA		Cooling			
Conn.				Temp. Class			
Frequency		Hz					
Insul Level		%		Total Mass		kg	
Impedance				Type of Oil			
Pos.	HV		HV		LV		
	V	A	V	A	V	A	
MADE by ABB 9952							



Serial numb.				Prod. year			
- phase				- Dry - Type Transformer			
Rated power (Onan)		Kva		Cooling			
Frequency		Hz		Environment Cl.			
Connection Symbol				Climate Cl.			
Insulation levels		Kv		Fire Cl.			
Impedance		%		Insul. Sys. Temp		°C	
Total Mass		Kg		Max. Wind. Temp		°C	
Pos.	HV		HV		LV		
	V	A	V	A	V	A	
MADE by ABB 9952							

16.6. ELECTROMAGNETIC COMPATIBILITY (EMC)

16.6.1. Definitions

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The International Electrotechnical Vocabulary (IEV) gives the following definition of EMC:

"The ability of an equipment or system to function satisfactorily in its *electromagnetic environment* without introducing intolerable *electromagnetic disturbances* to anything in that environment." [IEV 161-01-07]

Other relevant definitions are:

Electromagnetic disturbance

Any electromagnetic phenomenon which, by being present in the electromagnetic environment, can cause electrical equipment to depart from its intended performance [IEV 161-01-05, modified]

Electromagnetic interference (EMI)

Degradation of the performance of equipment, transmission channel or system caused by an electromagnetic disturbance.

NOTE The terms "electromagnetic disturbance" and "electromagnetic interference" denote respectively cause and effect, but they are often used indiscriminately. [IEV 161-01-06]

Disturbance level

The amount or magnitude of an electromagnetic disturbance, measured and evaluated in a specified way [IEV 161-03-01, modified]

Electromagnetic compatibility level

The specified electromagnetic disturbance level used as a reference level in a specified environment for co-ordination in the setting of emission and immunity limits

NOTE By convention, the compatibility level is chosen so that there is only a small probability that it will be exceeded by the actual disturbance level. [IEV 161-03-10, modified]

Immunity level

The maximum level of a given electromagnetic disturbance incident on a particular device, equipment or system for which it remains capable of operating at a required degree of performance [IEV 161-03-14]

16.6.2. Electromagnetic disturbances on transformers

Transformers may be exposed to various types of electromagnetic disturbances when operating in public and industrial power supply systems.

Disturbance phenomena to consider are:

- harmonics,
- inter-harmonics,
- overvoltages,
- voltage unbalance,
- overcurrents,
- power frequency variation.

Harmonics

Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the power frequency at which the supply system is designed to operate.

Equipment with a non-linear voltage/current characteristic cause current harmonics.

Harmonic currents produce harmonic voltage drops across the impedance of the network.

IEC 60076-1 Power transformers Part 1: General assumes that the wave shape of the supply voltage is approximately sinusoidal. This requirement is normally not critical in public supply systems but may have to be considered in installations with considerable convertor loading. If the total harmonic content exceeds 5% or the even harmonic content exceeds 1%, this should be specified in the enquiry and in the order.

Current harmonics influence the load losses and the temperature rise, which may need consideration in the transformer design.

In systems with considerable capacitive elements, like long cables or power factor correction capacitors, there is a risk that harmonics cause shunt and series resonance in the network, which in turn causes voltage magnification even at a point remote from the distorting load.

The magnetizing current of transformers contains harmonics due to the non-linear magnetizing characteristic. The magnetizing current is in normal operation small, in the order of 1% of the rated current of the transformers, and the influence of its harmonics is negligible. However, if the transformer core is saturated due to an applied voltage higher than the rated voltage, the magnetizing current and its harmonics will dramatically increase.

Interharmonics

Interharmonic currents and voltages have frequencies which are not an integer multiple of the fundamental frequency. They can appear as discrete frequencies or as a wide-band spectrum. The sources of interharmonics can be different types of convertors, induction motors, arc welding machines and arc furnaces.

Interharmonics may need consideration in the transformer design.

Overvoltages

Quasi-stationary or steady state overvoltage causing an increase of more than 5% in the flux density in the transformer core in relation to the core flux at rated voltage should be specified in the enquiry and in the order.

The saturation flux density of modern core steel is 2,03 Tesla. Further increase in the magnetic flux may cause unacceptable heating in structural details keeping the core together and in the tank. A dramatic increase in the magnetizing current and its harmonics will also take place.

The topic of temporary and transient overvoltages is treated in chapter 15.

Voltage unbalance

IEC 60076-1 Power transformers Part 1: General assumes that the three-phase supply voltage is approximately symmetrical in normal service conditions.

The predominant cause of voltage unbalance is unbalanced load. Due to the distorted voltage triangle the voltage across one or two phase windings will be higher than rated. Consequently the flux density in one or two limbs of the core will increase correspondingly. If saturation in these limbs is reached, unacceptable heating in structural details keeping the core together and in the tank may occur. Increase in the magnetizing current and its harmonics in the affected phases will be another consequence. The sound level of the transformer may also increase.

It is not possible to make a general rule regarding permitted unbalance for transformers. Each case must be treated individually. If the degree of unbalance is known before ordering the transformer, it will be possible to take it into account in the design. Before connecting a dominant single-phase load to an already existing transformer, it is recommended to analyse the situation first.

Overcurrents

IEC 60076-7 – Power transformers – Part 7: Loading guide for oil-immersed transformers (in process) and IEC 60905 Loading guide for dry-type transformers provide advice regarding overloading of transformers, continuously or intermittently.

Transformers may also be exposed to overcurrents due to short-circuits in the network. Such currents may amount to 10 – 20 times the rated current of the transformer or even more. Large pulsating mechanical forces will act on the windings and their supports during these currents. In addition the high current density in the windings will rapidly increase the winding temperature.

Transformers are designed to withstand certain short-circuit currents, but the duration of the currents must be limited to maximum 2 seconds by means of relays that disconnect the transformer from the energy sources, unless a longer duration is agreed in the contract.

Service experience indicates that transformers from experienced manufacturers seldom fails because of short-circuit currents.

Power frequency variation

In public supply systems the temporary frequency deviation from the nominal frequency is normally not more than ± 1 Hz. The steady-state deviation of frequency from the nominal frequency is much less.

A frequency of 49 Hz instead of 50 Hz will increase the flux density in the transformer core by 2% at the same applied voltage.

In supply systems isolated from public network (for example an island system) frequency variations up to $\pm 4\%$ are expected. In such cases the flux density in the transformer core may increase up to 4%, and this should be taken into account when designing the transformer.

The maximum disturbance level in a network may be derived from theoretical studies or measurements. The disturbance level is not a single value but varies statistically with location and time. Because of this variability it is often very difficult or even impossible to determine the real highest level of disturbance, which may appear very infrequently. It may, in general, not be economical to define the compatibility level in terms of this highest value to which most devices would not be exposed to most of the time.

It seems more appropriate to define the compatibility level as a value that only will be exceeded by the disturbance level in very few cases, for example 1 or 2%.

The compatibility of transformers regarding overvoltages and overcurrents is verified by means of various tests described in the IEC transformer standards 60076-3, 60076-5 and 60726. When performing thermal testing on convertor transformers, the effect of harmonic currents is taken into account according to IEC 61378-1.

16.6.3. Electromagnetic field in the vicinity of transformers

Distribution transformers with voltage ratio from medium to low voltage for supply to commercial and industrial consumers are often integrated into these consumers' buildings. The electromagnetic field from such transformers may disturb the performance of electronic equipment situated near by. Or in other words, the magnetic field may exceed the immunity level of the electronic equipment.

IEC 61000-2-7 "Electromagnetic compatibility (EMC) – Part 2: Environment – Section 7: Low frequency magnetic fields in various environments" refers results from measurements taken at an installation of a 315 kVA distribution transformer. The measurements were taken with field coils and are considerably influenced by the presence of harmonics. For this reason two values are stated for each ff, one at 50 Hz and one at 0 kHz to 2 kHz. Typical measured maximum values at various locations are given in the following table:

Location	Magnetic field [A/m]		Magnetic flux density in air [μ T]	
	50 Hz	0 kHz – 2 kHz	50 Hz	0 kHz – 2 kHz
Adjacent to transformer connections	200	300	250	380
Above transformer	15	60	20	75
Adjacent to low-voltage cables	20	70	25	90
Adjacent to but outside the roof	5	30	6	40

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The magnetic field was detectable up to approximately 10 m from the physical enclosure of the substation.

Practical experience from measurements of electromagnetic field around a transformer indicates that the measured values are considerably dependant on how the measurements are made. There is so far no international standard describing how measurements of the electromagnetic field around transformers shall be performed to achieve consistent results. Still the above example indicates the magnitude of the field that can be expected.

CENELEC report R014-001 "Guide for the evaluation of electromagnetic fields around power transformers" indicates formulas for calculation of field values for some simple geometric configurations.

In cases where the field exceeds the immunity levels of various kinds of electronic equipment in the vicinity of the transformer, appropriate shielding of the equipment or moving the equipment further away from the transformer can solve the problem. ABB has developed solutions for shielding cable boxes which reduce the electromagnetic field related to the LV cables and connections.

Contaminants on bushings of oil-immersed transformers and on windings of dry-type transformers may, especially in the presence of moisture, cause electrical discharges, which in turn may cause disturbance on electronic equipment. Appropriate routines for cleaning are recommended in section 4.3.6.

16.6.4. Effect of electromagnetic fields on humans

With regard to health hazards a magnetic flux density of 100 μT at 50 Hz seems to be considered as acceptable with high safety factor (250-500). For short time exposure the acceptable limit can be doubled.

Research on the effect of electric and magnetic fields on health is still not complete.

Attention should be paid to the possible influence of such fields on heart pacemakers.

16.7. UNITS AND CONVERSION TABLES

16.7.1. Basic SI units

<i>Quantity</i>	<i>Unit Symbol</i>	<i>Unit Name</i>
Length	m	metre
Mass	kg	kilogramme
Time	s	second
Electric current	A	ampere
Thermodynamic temperature	K	kelvin
Luminous intensity	cd	candela
Quantity of substance	mole	mole

16.7.2. Multiples and sub-multiples of units

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{12}	tera	T	10^{-2}	centi	c
10^9	giga	G	10^{-3}	milli	m
10^6	mega	M	10^{-6}	micro	μ
10^3	kilo	k	10^{-9}	nano	n
10^2	hecto	h	10^{-12}	pico	p
10^1	deka	da	10^{-15}	femto	f
10^{-1}	deci	d	10^{-18}	atto	a

16.7.3. Electrical and magnetic quantities

<i>Quantity</i>	<i>SI unit Name</i>	<i>Symbol</i>	<i>Other units</i>	<i>symbol</i>	<i>Relationship</i>
Electric current, magnetic potential difference	ampere	A			
Electric voltage, electric potential difference	volt	V			1 V = 1 W/A
Electric conductance	siemens	S			1 S = A/V
Electric resistance	ohm	Ω			1 Ω = 1/S

Quantity	SI unit Name	Symbol	Other units	symbol	Relationship
Quantity of electricity, electric charge	coulomb	C	ampere-hour	Ah	1 C = 1 As 1 Ah = 3600 As
Electric capacitance	farad	F			1 F = 1 C/V
Electric flux density	coulomb per square metre	C/m ²			
Electric field strength	volt per metre	V/m			
Magnetic flux	weber, volt-second	Wb, Vs			1 Wb = 1 Vs
Magnetic flux density, (induction)	tesla	T			1 T = 1 Wb/m ²
Inductance (permeance)	henry	H			1 H = 1 Vs/A = 1 Wb/A
Magnetic field strength	ampere per metre	A/m			

16.7.4. General electrotechnical symbols

16.7.4.1. Mathematical symbols for electrical quantities (general)

Symbol	Quantity	SI unit
Q	quantity of electricity, electric charge	C
E	electric field strength	V/m
D	electric flux density, electric displacement	C/m ²
U	electric potential difference	V
V, φ	electric potential	V
ε	absolute permittivity constant	F/m
ε_0	permittivity for vacuum $\varepsilon_0 = 8,8541817 \cdot 10^{-12}$ F/m	F/m
ε_r	relative permittivity	1
C	electric capacitance	F
I	electric current	A
J, S	electric current density	A/m ²
γ , σ	specific electric conductivity	S/m
ρ	specific electric resistance, resistivity	Ω m
G	electric conductance	S
R	electric resistance	Ω
E	electromotive force	V

16.7.4.2. Mathematical symbols for magnetic quantities (general)

Symbol	Quantity	SI unit
Φ	magnetic flux	Wb
B	magnetic induction	T
H	magnetic field strength, magnetizing field strength	A/m
F, F_m	magnetomotive force	A
U, U_m	magnetic potential difference	A
μ	absolute permeability	H/m
μ_0	absolute permeability for vacuum $\mu_0 = 4\pi \cdot 10^{-7} \cdot \text{H/m}$	H/m
μ_r	relative permeability	1
L	self inductance	H
M, L_{mn}	mutual inductance	H

16.7.4.3. Mathematical symbols for alternating-current

Symbol	Quantity	SI unit
S	apparent power	W, VA
P	active power	W
Q	reactive power	VA(r)
φ	phase difference	rad
λ	power factor = $P/S = \lambda$. For the special case of sinusoidal voltage and current $\lambda = \cos \varphi$	
δ	loss angle	rad
d	dissipation factor, $d = P/\sqrt{S^2 - P^2}$. For the special case of sinusoidal voltage and current $d = \tan \delta$.	
Z	impedance	Ω
R	resistance	Ω
X	reactance	Ω

16.8. LIST OF ABBREVIATIONS AND ACRONYMS

ABB	Asea Brown Boveri. www.abb.com
ANSI	American National Standards Institute
ATS	Auto transformer station
CbVV	Combined voltage variation
CE	Communauté Européenne. (European Conformity) www.ce-marking.org
CEN	Comite Europeen de Normalisation (European committee for standardization)
CENELEC	Comite Europeen de Normalisation Electrotechnique (European Committee for Electrotechnical Standardization)
CFVV	Constant flux voltage variation
DDP	Delivered duty paid ...
DDU	Delivered duty unpaid ...
DIN	Deutsches Institut für Normung e.V. (German Institute for standardisation)
DoC	Declaration of Conformity
EHV	Extra high voltage, above 420 kV and up to and including 800 kV
EMC	Electromagnetic compatibility
EXW	Ex works ...
FAT	Factory acceptance test

GIS	Gas-insulated switchgear
HV	High voltage
ICC	International Chamber of Commerce
IEC	International Electrotechnical Commission. www.iec.ch
IEEE	The Institute of Electrical and Electronics Engineers, Inc.
IEV	International Electrotechnical Vocabulary
INCOTERMS	Standard definitions of trade terms
IP	International Protection (IEC 60529)
ISO	International Organization for Standardization
LBOR	Load Break Immersed Switch – ABB product
LCA	Life cycle Assessment
LDT	Large distribution transformers
LI	Lightening impulse, full wave
LIC	Lightning impulse chopped on tail
LV	Low voltage
MDT	Medium distribution transformers
MTP	Mini-Three Phase Padmounted transformer
NA	Not applicable
NEMA	National Electrical Manufacturers Association www.nema.org
ONAF	Cooling: Oil natural. Air forced
ONAN	Cooling: Oil natural. Air natural
ORGALIME	General conditions. Limitation of responsibilities
PCB	Polychlorinated biphenyl
PD	Partial discharge
ppm	Parts Per Million
PTDT	Power Technology, Distribution Transformers
r.m.s.	Root mean square
SDT	Small distribution transformers
SI	Système Internationale d'Unites (International System of Units)
TGV	French high speed train
TOV	Temporary overvoltage
UCT	Underground commercial transformer
UHV	Ultra high voltage, above 800 kV
Um	Highest voltage for equipment
VDE	Verband der Elektrotechnik Elektronik Informationstechnik e.V (Association for Electrical, Electronic & Information Technologies)
VFVV	Variable flux voltage variation
VPE	Vacuum Pressure Encapsulated
VPI	Vacuum Pressure Impregnated
VSD	Variable speed drives

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16.11. OBTAINING COPIES OF THE HANDBOOK

Please contact your nearest ABB contact for obtaining a copy of the handbook.

See also www.abb.com/transformers.

Otherwise contact the ABB Transformers Communication Manager sonia.potsada@de.abb.com

17. BIBLIOGRAPHY

17.1. TRANSFORMER-RELEVANT STANDARDS

A number of transformer relevant standards are listed in this section. These standards are issued by the three different institutions IEC, CENELEC and ANSI/IEEE.

17.1.1. IEC standards

IEC stands for International Electrotechnical Commission, which was officially founded in 1906 in London, England, based on a proposal launched at a meeting in the International Electrical Congress in 1904 in St. Louis, USA.

The technical work in IEC is organised in technical committees (TCs), consisting of experts from the member countries in the different subjects. By 1914 the IEC had formed four technical committees to deal with nomenclature, symbols, rating of electrical machinery, and prime movers.

The First World War interrupted IEC work, which resumed in 1919 and by 1923 the number of technical committees had increased to 10.

In 1938 the IEC produced the first edition of the International Electrotechnical Vocabulary (IEV). The unification of electrotechnical terminology was one of the principal tasks allocated to the IEC by the St. Louis congress. In the early days, the Nomenclature Committee was engaged in pioneer work, as no comparable international technical vocabulary had yet been published and few national electrotechnical vocabularies existed. With its 2000 terms in French, English, German, Italian, Spanish and Esperanto, and its definitions in French and English, the IEV could rightly be considered as an outstanding achievement. It aroused wide interest among international technical organizations outside the electrotechnical field.

In September 1939 the IEC's activity came to a standstill because of the Second World War and did not resume for another six years.

From 1948 to 1980 the number of technical committees grew from 34 to 80 and began to include such new technologies as capacitors and resistors, semiconductor devices, electrical equipment in medical practice and maritime navigation and radio communication systems and equipment.

In 2001 the Commission published the most recent edition of the IEC Multilingual Dictionary. It is a compilation of the IEV, which now contains 18 500 electrotechnical concepts divided into 73 subject areas, containing full definitions in French and English and equivalent terms in 12 languages, including an index in German.

At present IEC have 62 member countries and technical committees for 110 different subjects. Some of the technical committees have several subcommittees. Including the subcommittees there are totally 174 technical committees.

Technical committee number 14 (TC14) deals with power transformers and reactors. This committee has 32 participating countries (P-members) and 10 observer countries (O-members). To be a P-member or an O-member is each country's own individual choice. Only the participating countries have the right and the commitment to vote on documents worked out by the committee and the right to participate in the working groups (WGs) preparing the standards.

A draft for an IEC standard needs at least 67 % of the voting P-members to obtain approval as an IEC standard. Each P-member has one vote. The present IEC standards prepared by TC14 have achieved a considerable higher percentage of votes in favour than 67. So the IEC transformer standards are based on a high degree of consensus among experts in the countries that are P-members in TC14, and they are extensively applied around the world.

The use of IEC standards is a voluntary matter. Contractual partners are free to use the IEC standards or anything else. They are also free to use parts of an IEC standard, to make exceptions from the standards or additional requirements. But as soon as an IEC standard has been made a part of a technical contract specification, the IEC standard becomes a legally binding document, except for deviations written in the contract.

The IEC standards do not prescribe how to design and produce transformers. So, to say that a transformer shall be or is designed and produced according to the IEC standards would be meaningless, or it would at least be imprecise use of language.

The IEC transformer standards describe certain tests the transformers shall be subjected to before delivery from the factory and state the acceptance criteria. The purpose of the tests is that transformers that have passed these tests shall have good prospects of a long life and high service reliability, when adequately protected and maintained. In this respect the IEC has been successful.

Transformers tested according to IEC standards are one of the most reliable components in electric power systems. Many transformers have been in service for more than half a century without problems worth mentioning.

However, In the Foreword of the standards the IEC states that the IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with one of its standards. Further the IEC draws attention to the possibility that some of the elements of its standards may be the subject of patent rights, and states that the IEC shall not be held responsible for identifying any or all such patent rights.

17.1.2. CENELEC standards

CENELEC stands for Comité Européen de Normalisation Electrotechnique, in English: European Committee for Electrotechnical Standardisation. It was created in 1973.

CENELEC standards (EN standards) are international standards prepared by working groups and approved by weighted voting among countries being members of the European Union (EU) and other countries included in the European Economic Area Agreement.

The CENELEC transformer standards are for a large part identical to the IEC standards with a few minor amendments.

However, CENELEC has also issued standards concerning transformer accessories, which have no corresponding IEC standards. An example is the series EN 50216-1 through 7 specifying detailed geometric dimensions and certain performance characteristics of items like gas relays, pressure devices, oil level and flow indicators, oil pumps. The purpose is to provide interchangeability and to remove technical trade barriers between CENELEC member countries. The latter is an EU target.

In line with this CENELEC member countries are bound to withdraw national standards conflicting with the EN standards and ratify the EN standards, either as they are or in a word for word translation. In public procurement there is an obligation to apply EN standards as the first priority standards as the base for the technical specification, according to The European Public Procurement Directive, if the prospective contract sum is above a certain limit.

CENELEC has also issued a number of Harmonization Documents (HD). Their formal status is practically the same as that of the EN standards. CENELEC has decided to phase out the Harmonization Documents and replace them by EN standards.

17.1.3. IEEE standards

IEEE stands for The Institute of Electrical and Electronics Engineers, Inc.

Contrary to the IEC standards, which are international standards, IEEE standards are national standards prepared and issued in the United States of America by the IEEE Societies. These standards are also sometimes used in other countries, without being ratified as national standards in those countries.

Like the IEC standards the use of IEEE Standards is wholly voluntary, and it becomes mandatory only when specified in a contractual relationship or when required by a duly constituted legal authority. The IEEE clearly indicates that the existence of an IEEE Standard does not imply that there are no other ways to deal with matters related to the scope of the IEEE standard.

In some recent standards the IEEE expressly states that "The IEEE disclaims liability for any personal injury, property or other damage, of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the publication, use of, or reliance upon this, or any other IEEE Standard document."

IEEE standards also contain a reservation regarding patent rights, saying:

"Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention."

17.1.4. Comparison between ANSI/IEEE standards and IEC standards

The purpose of this section is to point out some basic, essential differences between transformer standards issued by the two institutions. This is not meant to be an exhaustive list of differences. To avoid possible unpleasant surprises, contract partners need to perform a detailed study of the standards specified in the enquiry or the contract.

The IEC standards prepared by TC14 are found in the series 60076- with sub-numbers 1, 2, 3 and so on. convertor transformers are treated in the 60378- series and tap-changers in 60214-.

The basic American standards are the general C57.12.00, C57.12.80 taking care of the terminology and C57.12.90 treating the testing topic. In addition comes a list of standards specifying outside features like for example terminal arrangement, especially for smaller power transformers for distribution and for different erection (pad-mounted, pole-mounted, underground) and for different ranges of power and voltage rating.

With the exception of the minimum clearances between live parts of the bushings and between these and earth, the IEC standards do not specify outside details. These items are left to national standards or to customer specifications. So the outside appearance of transformers in for example Germany and Great Britain may be quite different, although they all fulfill the IEC requirements. Looking at the active part there is seldom much principal difference. (The active part of core-type and shell-type do look very different, but neither the IEC nor the ANSI/IEEE standards distinguish between these two types, except for the mechanical forces during short circuit).

There are some basic differences between the IEC and the ANSI/IEEE standards we would like to emphasize.

17.1.4.1. Definition of power rating (rated kilovoltamperes)

IEEE Std C57.12.00-2000 has the following definition:

"The rated kVA of a transformer shall be the output that can be delivered for the time specified at rated secondary voltage and rated frequency without exceeding the specified temperature-rise limitations under prescribed conditions of test, and within the limitations of established standards."

Paragraph 5.5.2 Voltage ratings states:

"The voltage ratings shall be at no load and shall be based on the turn ratio."

When a transformer is loaded there is a voltage drop in the transformer. To achieve rated voltage at the secondary terminals, the voltage at the primary side has to be raised above the rated value to compensate for the voltage drop in the transformer. The voltage drop depends on the short circuit impedance of the transformer, the load current and the power factor of the load.

Under paragraph 4.1 Usual service conditions, the load power factor is assumed to be 0.8 or higher. The transformer designer has to take these circumstances into account to avoid that the flux density does not become too high when the power flow direction is such that the secondary winding is not the inmost winding on the core.

Paragraph 4.1 specifies also that neither the voltage nor the volts per hertz are assumed to exceed 110 % of rated values. This means that the transformer core must in any case be able to carry a magnetic flux that is 10 % higher than the flux at rated voltage in no load condition.

IEC 60076-1 (1993-03) has the following definition:

"3.4.6 rated power (S_r): A conventional value of apparent power assigned to a winding which, together with the rated voltage of the winding, determines its rated current."

and states further in a NOTE:

"Both windings of a two-winding transformer have the same rated power which by definition is the rated power of the whole transformer."

Paragraph 3.4.3 defines the rated voltage of a winding (U_r) as:

"The voltage assigned to be applied, or developed at no-load, between the terminals of an untapped winding, or of a tapped winding connected to the principal tapping (see 3.5.2). For a three-phase winding it is the voltage between line terminals. [IEV 421-04-01, modified]"

In a NOTE it is added:

"The rated voltages of all windings appear simultaneously at no-load when the voltage applied to one of them has its rated value."

The rated power is then a function of the product of rated voltage and rated current. The rated voltage can be applied to the primary terminals, and rated current will flow in the primary winding when the secondary winding is loaded with its rated current. The power applied to the primary winding is then equal to the rated power. However, the secondary voltage will be different from the rated secondary voltage and consequently also the power delivered from the secondary winding will be different from the rated power of the transformer, due to the voltage drop in the transformer.

This implies that the rated power of the transformer according to the IEC definitions is a value of apparent power input to the transformer, including its own absorption of active and reactive power (while the rated power according to the IEEE definitions is a value of apparent power delivered from the secondary side).

This implies further that when IEC standards apply, the user has to consider the voltage drop in the transformer in various expected service conditions before determining the rated voltages of the transformer.

In paragraph 4.4 IEC60076-1 (1993-03) says that:

“...a transformer shall be capable of continuous service without damage under conditions of ‘overfluxing’ where the ratio of voltage over frequency exceeds the corresponding ratio at rated voltage and rated frequency by no more than 5 %.” (IEEE 10 %).

17.1.4.2. Reference temperature for load losses

The reference temperature for the load losses in IEEE is 85 °C, while it is 75 °C in IEC. This implies that the load losses in one and the same transformer will appear higher when the IEEE standards apply than when IEC standards apply.

When optimising a transformer design based on given capitalised values for the losses, the spending of materials will tend to be higher when the IEEE standards apply than when IEC standards apply.

17.1.4.3. Uncertainty in measurements

IEEE Std C57.12.00-2000 specifies in Table 21 accuracy requirements in the measurement of losses, voltage, current, resistance and temperature. Before tendering on the base of this IEEE standard, the tenderer must carefully evaluate his measurement equipment to see whether he is able to fulfill these requirements.

IEC has no concrete numeric requirements on this topic, but says in the Application guide 60076-8, paragraph 10.1 that:

“Statements of limits or uncertainty shall be available and these statements shall be supported by a documented traceability (see ISO 9001).”

17.1.4.4. Dielectric testing

When lightning impulse test is specified, testing with chopped wave (chopped on the tail) is a compulsory part of the test in the IEEE standard. In IEC chopped wave test is only made when specified.

A transformer withstanding a full wave test may not without further notice withstand a chopped wave because the chopping will involve a rapid fall in the voltage, which may cause more severe stresses in the winding than during the full wave test. This is a test that may express something about the transformer's ability to withstand the stresses that arise when re-ignitions occur in the circuitbreakers during contact separation when opening the circuitbreaker.

IEEE has also an option for a front of wave test. That is a voltage impulse chopped on the front before the voltage surge has reached its crest value. This test is only made when specified. IEC does not include this kind of test.

17.1.4.5. Short circuit requirements and testing

The differences between IEC and IEEE in requirements regarding ability to withstand short circuit currents and in testing to verify this ability are not large. However, there are some details where the standards deviate from each other, and some of these disparities will be listed in the following.

- IEEE standards divide the transformers into four categories while IEC has three categories, based on the kVA rating in both standards. Each category is subject to somewhat different requirements.
- In cases where the short circuit power of the systems to be connected to the transformer is not specified, these values shall be taken from tables in the standards. The system short circuit apparent power is considerably higher in the IEEE standard than according to "current European practice" in IEC 60076-5 (2000). However, the transformer impedance is normally much higher than the system impedance, so the difference in short circuit current flowing through the transformer will be quite modest.
- The algorithm for calculating the maximum asymmetric peak current is the same in both standards. The asymmetry increases with increasing x/r , where x and r are respectively the total reactance and the total resistance in the whole circuit. For $x/r > 14$ IEC states a maximum value for the peak factor, while IEEE does not contain such a limitation. The consequence of this may in some cases be that in very large transformers the cross section of the winding conductor must be a little larger to fulfill the short circuit requirements in IEEE compared to those in IEC. The manufacturing cost will then be somewhat higher. However, this may be compensated by lower losses.
- IEEE specifies six "shots" per phase, two of those shall be with full asymmetry. IEC specifies three "shots" per phase with full asymmetry on all three "shots". It is hard to judge which of the two test procedures is the toughest one for the transformer.
- Both IEEE and IEC standards contain a list of criteria that must be fulfilled to state that the transformer has passed the test. These criteria are more or less the same in both standards with one exception. IEEE requires for the largest transformers (category II, III and IV with circular windings) not more than 2 % difference in the ohmic value of the transformer's short circuit impedance measured before and after the test. The corresponding requirement in IEC for transformers with apparent power rating above 100 MVA is 1 %. IEC has the toughest requirement at this point.
- Both IEEE and IEC standards have a requirement regarding the winding conductor temperature rise during short circuit current. The temperature rise shall be calculated based on the stationary value of the short circuit current and its duration. The algorithm is basically the same in both standards, calculating as if no heat transfer to the environment takes place during the short time the short circuit current is flowing. IEC assumes that all the heat developed is stored in the conductor material, copper or aluminum. IEEE takes in addition into account that some heat is also stored in the insulation of the conductor. The maximum permitted temperature rise for each winding is the same in both standards, 250 °C for copper and 200 °C for aluminum. However, IEEE permits also 250 °C for certain aluminum alloys. IEC specifies that the duration of the current to be used when calculating this temperature rise shall be 2 s unless a different duration is specified. This duration is in most cases shorter in the IEEE standards.
- In an amendment (in process) to IEC 60076-5 a method is described, which shows how the ability of the transformer to withstand the mechanical forces during short circuit may be verified by means of calculation and comparison with a similar transformer that has passed a short circuit test.
IEEE has no corresponding method.
- IEEE C57.12.00-2000 specifies that the winding hot spot temperature rise shall not exceed 80 °C.

IEC 60076-2 (1993-04) has no requirement on hot spot winding temperature rise.

IEC and IEEE have expressed the intention gradually to decrease or remove basic differences between their standards. It is envisaged that a closer co-operation between the two organizations will make the future standardization work more cost efficient. Besides that it is recognized that basic physical phenomena are the same all over the world.

Concerning the transformer subjects the first approach in this respect is already in process. IEEE has already issued a standard on phase-shifting transformers, IEEE Std. C57.135-2001. It would seem unreasonable that the IEC, which so far has no standard for this type of transformers, should start working on this topic from scratch. So, the IEC has sent this IEEE standard to the National committees of the IEC for a preliminary vote with the possibility to comment and suggest changes. If this standard achieves approval within the IEC, the standard will be issued in a new edition with the logo of both organizations on the front page.

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Power transformers - Part 11: Dry-type transformers
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Insulating liquids – Determination of the breakdown voltage at power frequency – Test method
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¹⁾ New edition in process

¹⁾ New edition in process

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- IEC 60970 (1989-06)
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- EN 50216-2: 2002 +A1: 2002
 - Power transformer and reactor fittings – Part 2: Gas and oil actuated relay for liquid immersed transformers and reactors with conservator
- EN 50216-3: 2002 +A1: 2002
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 - Power transformer and reactor fittings – Part 4: Basic accessories (earthing terminal, drain and filling devices, thermometer pocket, wheel assembly)
- EN 50216-5: 2002 +A1: 2002
 - Power transformer and reactor fittings – Part 5: Liquid level, pressure devices and flow indicators
- EN 50216-6: 2002
 - Power transformer and reactor fittings – Part 6: Cooling equipment – Removable radiators for oil-immersed transformers
- EN 50216-7: 2002
 - Power transformer and reactor fittings – Part 7: Electric pumps for transformer oil
- EN 50243: 2002
 - Outdoor bushings for 24 kV and 36 kV and for 5 kA and 8 kA, for liquid filled transformers
- EN 50299: 2002
 - Oil-immersed cable connection assemblies for transformers and reactors having highest voltage for equipment U_m from 72,5 kV to 550 kV
- EN 50336: 2002
 - Bushings for transformers and reactor cable boxes not exceeding 36 kV
- EN 50386: 2002
 - Bushings up to 1 kV and from 250 A to 5 kA, for liquid filled transformers
- EN 50387: 2002
 - Busbar bushings up to 1 kV and from 1,25 kA to 5 kA, for liquid filled transformers
- EN 60071-1: 1995
 - Insulation co-ordination – Part 1: Definitions, principles and rules
- EN 60071-1: 1995 +A1: 2000
- EN 60071-2: 1997
 - Insulation co-ordination – Part 2: Application Guide
- EN 60071-2: 1997 +A12: 2002
- EN 60076-1: 1997
 - Power transformers – Part 1: General
- EN 60076-1: 1997 +A11: 1997
- EN 60076-2: 1997
 - Power transformers – Part 2: Temperature rise
- EN 60076-3: 2001
 - Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air

- EN 60076-4: 2002
Power transformers – Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors
- EN 60076-5: 2000
Power transformers – Part 5: Ability to withstand short-circuit
- EN 60076-10: 2001
Power transformers – Part 10: Determination of sound levels
- EN60137: 1996
Insulated bushing for alternating voltage above 1 kV
- EN60156: 1995
Insulating liquids – Determination of the breakdown voltage at power frequency – Test method
- EN 60214: 1997
On-load tap-changers
- EN 60214-1: 2003
Tap-changers – Part 1: Performance requirements and test methods
- EN 60567: 1992
Guide for the sampling of gases and of oil from oil-filled electrical equipment and for the analysis of free and dissolved gases
- EN 60599: 1999
Mineral oil-impregnated electrical equipment in service – Guide to the interpretation of dissolved and free gas analysis
- EN 60726: 2003
Dry-type transformers
- EN 60814: 1997
Insulating liquids – oil-impregnated paper and pressboard – Determination of water by automatic coulometric Karl Fischer titration
- EN 61065: 1993
Method for evaluating the low temperature flow properties of mineral insulating oils after ageing
- EN 61099: 1992
Specification for unused synthetic organic esters for electrical purposes
- EN 61100: 1992
Classification of insulating liquids according to fire point and net calorific value
- EN 61125: 1993
Unused hydrocarbon-based insulating liquids – Test methods for evaluating the oxidation stability
- EN 61197: 1994
Insulating liquids – Linear flame propagation – Test method using a glass-fibre tape
- EN 61203: 1994
Synthetic organic esters for electrical purposes – Guide for maintenance of transformer esters in equipment
- En 61378-1: 1998 + corrigendum Nov. 1998
Convertor transformers – Part 1: Transformers for industrial applications
- EN 61620: 1999
Insulating liquids – Determination of dielectric dissipation factor by measurement of the conductance and capacitance – Test method
- HD 428.1 S1: 1992 +A1: 1995
Three-phase oil-immersed distribution transformers 50Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV – Part 1: General requirements and requirements for transformers with highest voltage for equipment not exceeding 24 kV

HD 428.2.1 S1: 1994

Three-phase oil-immersed distribution transformers 50Hz, from 50 kVA to 2,5 MVA with highest for equipment not exceeding 36 kV – Part 2: Distribution transformers with cable boxes on the high-voltage and/or low-voltage side – Section 1: General requirements

HD 428.2.2 S1: 1997

Three-phase oil-immersed distribution transformers 50Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV – Part 2: Distribution transformers with cable boxes on the high-voltage and/or low-voltage side – Section 2: Cable boxes type 1 for use on distribution transformers meeting the requirements of HD 428.2.1

HD 428.2.3 S1: 1998

Three-phase oil-immersed distribution transformers 50Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV – Part 2: Distribution transformers with cable boxes on the high-voltage and/or low-voltage side – Section 3: Cable boxes type 2 for use on distribution transformers meeting the requirements of HD 428.2.1

HD 428.3 S1: 1994

Three-phase oil-immersed distribution transformers 50Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV – Part 3: Supplementary requirements for transformers with highest voltage for equipment equal to 36 kV

HD 428.4 S1: 1994

Three-phase oil-immersed distribution transformers 50Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV – Part 4: Determination of power rating of a transformer loaded with non-sinusoidal currents

HD 428.6 S1: 2002

Three-phase oil-immersed distribution transformers 50Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV – Part 6: Requirements and tests concerning pressurised corrugated tanks

HD 565 S1: 1993

Specification for silicone liquids for electrical purposes

HD 637 S1: 1999

Power installations exceeding 1 kV a.c.

R014-001: 1999

Guide for the evaluation of electromagnetic fields around power transformers

17.1.7. ANSI/IEEE Standards

- IEEE Std 259 – 1999TM
IEEE Standard Test Procedure for Evaluation of Systems of Insulation for Dry-type Specialty and General Purpose Transformers
- IEEE Std 637 – 1985 (R1992,2002)TM
IEEE Guide for the Reclamation of Insulating Oil and Criteria for Use
- IEEE Std 638 – 1992 (R1999)TM
IEEE Standard for Qualification of Class 1E Transformers for Nuclear Generating Stations
- IEEE Std 1276 – 1997TM
IEEE Guide for the Application of High-Temperature Materials in Liquid-Immersed Power Transformers
- IEEE Std 1388 – 2000TM
IEEE Standards for Electronic Reporting of Transformer Tests
- IEEE Std 1538 – 2000TM
IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Filled Transformers
- IEEE Std C57.12.00 – 2000TM
IEEE Standard General requirements for – Liquid-Immersed Distribution, Power, and Regulating Transformatmers
- IEEE Std C57.12.01 – 1998TM
IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid-Cast and/or Resin-Encapsulated Windings
- ANSI C57.12.10-1997
230 kV and Below 833 / 958 through 8333 / 10 417 kVA, Single-Phase, and 750 / 862 through 60 000 / 80 000 /100 000 kVA, Three-Phase Without Load Tap Changing; and 3750 / 4687 through 60 000 / 80 000 / 100 000 kVA with Load Tap Changing— Safety Requirement
- IEEE C57.12.20 – 1997TM
American National Standard for Overhead Distribution Transformers 500 kVA and smaller: High Voltage, 34500 V and below: Low Voltage 7970/13800 Y V and below – Requirements
- IEEE Std C57.12.21 – 1992TM
American National Standard Requirements for Pad-Mounted, Compartmental-Type, Self-Cooled, Single-Phase Distribution Transformers With High Voltage Bushings; High-voltage,34500 GRD/19920 Volts and Below; Low-Voltage, 240/120 volts; 167 kVA and Smaller
- IEEE Std C57.12.22 – 1993 (R1998)TM
American National Standard for Transformers – Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers with High Voltage Bushings, 2500 kVA and Smaller, High-Voltage,34500 GrdY/19920 Volts and Below; Low-Voltage, 480 Volts and Below – Requirements
- IEEE Std C57.12.23 – 2002TM
IEEE Standard for Underground Type, Self-Cooled, Single-Phase, Distribution Transformers with Separable Insulated High-Voltage Connectors; High Voltage 25000 V and Below, Low Voltage 600 V and Below, 167 kVA and Smaller
- IEEE Std C57.12.24 – 2000TM
American National Standard for Transformors – Underground-Type, Three-Phase Distribution Transformers, 2500 kVA and Smaller; Voltage, 34500 GrdY/19920 Volts and below; Low Voltage, 480 Volts and Below – Requirements
- IEEE Std C57.12.25.-. 1990TM
American National Standard for Transformers – Pad-Mounted, Compartmental-Type, Self-Cooled, Single-Phase Distribution Transformers with Separable Insulated High-Voltage Connectors, High-voltage,34500 GrdY/19920 Volts and Below; Low-Voltage, 240/120 volts; 167 kVA and Smaller-Requirements

- IEEE Std C57.12.26 – 1992TM
IEEE Standard for Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers for Use with Separable Insulated High-Voltage Connectors (34500 GrdY/19920 Volts and Below; 2500 kVA and Smaller)
- IEEE Std C57.12.28 – 1999TM
American National Standard Pad-Mounted equipment – Enclosed Integrity
- IEEE Std C57.12.29 – 1991TM
American National Standard Switchgear and Transformers-Pad-Mounted Equipment-Enclosure Integrity for Coastal Environments
- IEEE Std C57.12.29 – 1999TM Errata
American National Standard Pad-Mounted Equipment-Enclosure Integrity for Coastal Environments (Replacement Figures Version)
- IEEE Std C57.12.31 – 2002TM
IEEE Standard for Pole mounted Equipment – Enclosure Integrity
- IEEE Std C57.12.32 – 2002TM
IEEE Standard for Submersible Equipment- Enclosure Integrity
- IEEE Std C57.12.35 – 1996TM
IEEE Standard for Bar Coding for Distribution Transformers
- IEEE Std C57.12.40 – 2000TM
American National Standard for Secondary Network Transformers Subway and Vault Types (Liquid Immersed) – Requirements
- IEEE Std 2C57.12.44 – 2000TM
IEEE Standard Requirements for Secondary Network Protectors
- IEEE Std C57.12.50 – 1981TM (R1998)
American National Standard Requirements for Ventilated Dry-Type Distribution Transformers, 1 to 500 kVA, Single-Phase, and 15 kVA, Three-Phase, with High-Voltage 601 to 34500 Volts, Low Voltage 120 to 600 Volts
- IEEE Std C57.12.51 – 1981TM (R1998)
American National Standard Requirements for Ventilated Dry-Type Distribution Transformers, 501 kVA and Larger, Three-Phase, with High-Voltage 601 to 34500 Volts, Low Voltage 208Y/120 to 4160 Volts
- IEEE Std C57.12.52 – 1981TM (R1998)
American National Standard Requirements for Sealed Dry-Type Distribution Transformers, 501 kVA and Larger, Three-Phase, with High-Voltage 601 to 34500 Volts, Low Voltage 208Y/120 to 4160 Volts
- IEEE Std C57.12.55 – 1987TM (R1998)
American National Standard Requirements for Transformers - Dry-Type Transformers Used in Unit Installations, Including Substations, Conformance Standard
- IEEE Std C57.12.56 – 1986TM (R1998)
IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Ventilated Dry-Type Power and Distribution Transformers
- IEEE Std C57.12.58 – 1991TM
IEEE Guide for Conducting a Transient Voltage Analysis of a Dry-Type Transformer Coil
- IEEE Std C57.12.59 – 2001TM
IEEE Guide for Dry-Type Transformer Through-Fault Current Duration
- IEEE Std C57.12.60 – 1998TM
IEEE Guide for Test Procedures for Thermal Evaluation of Insulation Systems for Solid-Cast and Resin-Encapsulated Power and Distribution Transformers
- IEEE Std C57.12.70 – 2000TM
IEEE Standard Terminal Markings and Connections for Distribution and Power transformers
- IEEE Std C57.12.80 – 2002TM
IEEE Standard Terminology for Power and Distribution Transformers

- IEEE Std C57.12.90 – 1999TM
IEEE Standard test Code for Liquid-Immersed Distribution, Power and Regulating Transformers and IEEE Guide for Short Circuit Testing of Distribution and Power Transformers
- IEEE Std C57.12.91 – 2001TM
IEEE Standard Test Code for Dry-Type Distribution and Power Transformers
- IEEE Std C57.18.10 – 1998TM
IEEE Standard Practices and Requirements for Semiconductor Rectifier Transformers
- IEEE Std C57.19.00 – 1991TM (R1997)
IEEE Standard General Requirements and Test Procedures for Outdoor Power Apparatus Bushings
- IEEE Std C57.19.01 – 2000TM
IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings
- IEEE Std C57.19.03 – 1996TM (R2002)
IEEE Standard Requirements, Terminology, and Test Code for Bushings for DC Applications
- IEEE Std C57.19.100 – 1995TM
IEEE Guide for Application of Power Apparatus Bushings
- IEEE Std C57.91 – 1995TM (R2002)
IEEE Guide for Loading Mineral-Oil-Immersed Transformers
- IEEE Std C57.91 – 1995/Cor 1 – 2002TM
IEEE Guide for Loading Mineral-Oil-Immersed Transformers Corrigendum 1 (Corrigendum to IEEE C57.91 – 1995)TM
- IEEE Std C57.93 – 1995TM
IEEE Guide for Installation of Liquid-Immersed Power transformers
- IEEE C57.94 – 1982 (R1987/2000)TM
IEEE Recommended Practice for the Installation, Application, Operation, and Maintenance of Dry-Type General Purpose Distribution and Power Transformers
- IEEE Std C57.96 – 1999TM
IEEE Guide for Loading Dry-Type Distribution and Power Transformers
- IEEE C57.98 – 1993 (R1999)TM
IEEE Guide for Impulse Tests
- IEEE Std C57.100 – 1999TM
IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers
- IEEE Std C57.104 – 1991TM
IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers
- IEEE Std C57.105 – 1978TM (R1999)
IEEE Guide for the Application of Transformer Connections in Three-Phase Distribution Systems
- IEEE Std C57.106TM – 2002TM
IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment
- IEEE Std C57.111 – 1989TM (R1995)
IEEE Guide for Acceptance of Silicone Insulating Fluids and Its Maintenance in Transformers
- IEEE Std C57.113 – 1991TM (R2002)
IEEE Guide for Partial Discharge Measurement in Liquid-Filled Transformers and Shunt Reactors
- IEEE Std C57.116 – 1989TM (R1994,2002)
IEEE Guide for Transformers Directly Connected to Generators
- IEEE Std C57.120-1991TM
IEEE Loss Evaluation Guide for Power Transformers and Reactors

- IEEE Std C57.121 – 1998TM
IEEE Guide for Acceptance and Maintenance of Less Flammable Hydrocarbon Fluid in Transformers
- IEEE Std C57.123 – 2002TM
IEEE Guide for Transformer Loss Measurement
- IEEE Std C57.124 – 1991TM (R1996,2002)
IEEE Recommended Practice for the Detection of Partial Discharge and the Measurement of Apparent Charge in Dry-Type Transformers
- IEEE Std C57.125 – 1991 (R1998)TM
IEEE Guide for Failure Investigation, Documentation and analysis for Power Transformers and Shunt Reactors
- IEEE Std C57.127 – 2000TM
IEEE Trial-Use Guide for the Detection of Acoustic Emissions from Partial Discharges in Oil-Immersed Power Transformers
- IEEE Std. C57.129 – 1999TM
IEEE Standard General Requirements and Test Code for Oil-Immersed HVDC Converter Transformers
- IEEE Std C57.131 – 1995TM
IEEE Standard Requirements for Load Tap Changers
- IEEE Std C57.134 – 2000TM
IEEE Guide for Determination of Hottest-Spot Temperature in Dry-Type Transformers
- IEEE Std C57.135 – 2001TM
IEEE Guide for the Application, Specification, and Testing of Phase-Shifting Transformers
- IEEE Std C57.136 – 2000TM
IEEE Guide for Sound Level Abatement and Determination for Liquid-immersed Power Transformers and Shunt Reactors Ratings Over 500 kVA
- IEEE Std C57.138 – 1998TM
IEEE Recommended Practice for Routine Impulse Test for Distribution Transformers

17.2. OTHER RELEVANT STANDARDS AND LITTERATURE

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- [2] R. Wilhelm and M. Waters: Neutral Grounding in High-Voltage Transmission, Elsevier Publishing Company, 1956.
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- [4] ABB Catalogue publication 1HSM 9543 22-01en, Controlled Switching Buyer's Guide, Edition 1, 2004-05
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- [6] Giorgio Bertagnolli : -SHORT-CIRCUIT DUTY OF POWER TRANSFORMERS – THE ABB APPROACH
- [7] Rüdenberg: Elektrische Schaltvorgänge 5. Auflage 1974
ISBN 3-540-05766-8 Springer-Verlag Berlin Heidelberg New York
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- [8] Herbert Baatz: Überspannungen in Energieversorgungsnetzen
1956 Springer-Verlag
- [9] ABB Switchgear Manual, 10th edition
- [10] ISO 9001:2000 Quality management systems. Requirements
- [11] EN 45014 General criteria for supplier's declaration of conformity
- [12] 89/336/EEC Electromagnetic compatibility
- [13] 73/23/EEC Low voltage equipment
- [14] 98/37/EC Safety of machinery
- [15] IEC 421-01-01 Electrotechnical Vocabulary
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ISBN 3-00-010400-3
- [17] ABB, Åke Carlson: Power Transformer Design Fundamentals
- [18] ABB, Åke Carlson: Power System Fundamentals

18. Extracts from

IEC 61936-1 (2002-10) POWER INSTALLATIONS EXCEEDING 1 kV A.C. – PART 1: COMMON RULES

The information given in this section is an extract from IEC 61936-1 (2002-10) Power installations exceeding 1 kV a.c. Common rules .

For full text, see the relevant standard. The numbering follows the numbering in the standard with preceding Re.

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Re. 4 FUNDAMENTAL REQUIREMENTS

Re. 4.1 General

Installations and equipment shall be capable of withstanding electrical, mechanical, climatic and environmental influences anticipated on site.

The relevant laws or regulations of an authority having jurisdiction shall have precedence.

Re. 5 INSULATION

As conventional (air insulated) installations cannot be impulse tested, the installation requires minimum clearances between live parts and earth and between live parts of phases in order to avoid flashover below the impulse withstand level specified for individual tested components of the installation.

Insulation coordination shall be in accordance with IEC 60071-1.

Table 1 – Minimum clearances in air – Voltage range I (1 kV < U_m ≤ 245 kV

Voltage range	Nominal voltage of system	Highest voltage for equipment	Rated short-duration power-frequency withstand voltage	Rated lightning impulse withstand voltage ^a	Minimum phase-to-earth and phase-to-phase clearance, <i>N</i> ^c		
	<i>U</i> _n r.m.s.	<i>U</i> _m r.m.s.	r.m.s.	1,2/50 μs (peak value)	Indoor installations	Outdoor installations	
	kV	kV	kV	kV	mm	mm	
I	3	3,6	10	20 40	60 60	120 120	
	6	7,2	20	40 60	60 90	120 120	
	10	12	28	60 75 95	90 120 160	150 150 160	
	15	17,5	38	75 95	120 160	160 160	
	20	24	50	95 125 145	160 220 270		
	30	36	70	145 170	270 320		
	45	52	95	250	480		
	66	72,5	140	325	630		
	110	123	185 ^b 230	450 550	900 1 100		
	132	145	185 ^b 230 275	450 ^b 550 650	900 1 100 1 300		
	150	170	230 ^b 275 325	550 ^b 650 750	1 100 1 300 1 500		
	220	245	275 ^b 325 ^b 360 395 460	650 ^b 750 ^b 850 950 1 050	1 300 1 500 1 700 1 900 2 100		
	a	The rated lightning impulse is applicable to phase-to-phase and phase-to-earth.					
	b	If values are considered insufficient to prove that the required phase-to-phase withstand voltages are met, additional phase-to-phase withstand tests are needed.					
	c	For rod-structure.					

Re. 6 EQUIPMENT

Re. 6.1 General requirements

Re. 6.1.1 Selection

Equipment shall be selected and installed to satisfy the following requirements:

- a) safe construction when properly assembled, installed and connected to supply;
- b) safe and proper performance taking into account the external influences that can be expected at the intended location;
- c) safe and proper performance during normal operation and in the event of reasonably expected conditions of overload, abnormal operation and fault, without resulting in damage that would render the equipment unsafe;
- d) protection of personnel during use and maintenance of the equipment.

Re. 7 INSTALLATIONS

Re. 7.1 General requirements

This clause specifies only general requirements for the installations regarding choice of circuit arrangement, circuit documentation, transport routes, lighting, operational safety and labelling.

Distances, clearances and dimensions specified are the minimum values permitted for safe operation. They are generally based on the minimum values given in the former national standards of the IEC members. A user may specify higher values if necessary.

NOTE For minimum clearances (N) of live parts, refer to 5.3 and to tables 1 and 2 and annex A.

National standards and regulations may require the use of higher clearance values.

Where an existing installation is to be extended, the requirements applicable at the time of its design and erection may be specified as an alternative.

The relevant standards for operation of electrical (power) installations shall additionally be taken into account. Operating procedures shall be agreed upon between manufacturer and user. Where applicable, the documentation shall be provided with each installation to allow erection, commissioning, operation, maintenance and environmental protection.

The extent of the documentation shall be agreed upon between the supplier and the user.

Diagrams, charts and tables, if any, shall be prepared in accordance with IEC 60617 and IEC 61082.

Re. 7.1.6 Operational safety

Operational safety installations shall be designed so that the escape and rescue paths and the emergency exit can be safely used in the event of a fire, and that protection and environmental compatibility are ensured.

Where necessary, installations themselves shall be protected against fire hazard, flooding and contamination. If required, additional measures shall be taken to protect important installations against the effects of road traffic (salt spray, vehicle accident).

Re. 8 SAFETY MEASURES

Installations shall be constructed in such a way as to enable the operating and maintenance personnel to circulate and intervene within the framework of their duties and authorizations, according to circumstances, at any point of the installation.

Specific maintenance work, preparation and repair work, which involve working in the vicinity of live parts or actual work on live parts, are carried out observing the rules, procedures and work distances as defined in national standards and regulations.

Re. 8. 6 Protection against fire

Re. 8.6.1 General

Relevant national, provincial and local fire protection regulations shall be taken into account in the design of the installation.

NOTE Fire hazard and fire risk of electrical equipment is separated into two categories: fire victim and fire origin. Precautions for each category should be taken into account in the installation requirements.

- a) Precautions to fire victim:
 - i) space separation from origin of fire;
 - ii) flame propagation prevention:
 - grading,
 - liquid containment,
 - fire barriers (e.g. REI fire-resistant materials 60/90),
 - extinguishing system;
- b) Precautions to fire origin:
 - i) electrical protection;
 - ii) thermal protection;
 - iii) pressure protection;
 - iv) fire resistant materials.

Care shall be taken that, in the event of fire, the escape and rescue paths and the emergency exits can be used (see 7.1.6).

The user or owner of the installation shall specify any requirement for fire extinguishing equipment.

Automatic devices to protect against equipment burning due to severe overheating, overloading and faults (internal/external) shall be provided, depending on the size and significance of the installation.

Equipment in which there is a potential for sparks, arcing, explosion or high temperature, for example electrical machines, transformers, resistors, switches and fuses, shall not be used in operating areas subject to fire hazard unless the construction of this equipment is such that flammable materials cannot be ignited by them.

If this cannot be ensured, special precautions, for example fire walls, fire-resistant separations, vaults, enclosures and containment, are necessary.

Re. 8.6.2 Transformers, reactors

In the following subclauses, the word 'transformer' represents 'transformers and reactors'.

For the identification of coolant types, see 6.2.2.2. IEC 61100 classifies insulating liquids according to fire point and net caloric value (heat of combustion). IEC 60726 classifies dry-type transformers in terms of their behaviour when exposed to fire.

The fire hazard associated with transformers of outdoor and indoor installations is dependent on the rating of the equipment, the volume and type of insulating mediums, the type and proximity and exposure of nearby equipment and structures. The use of one or more recognized safeguard measures shall be used in accordance with the evaluation of the risk.

NOTE For definition of risk, see ISO/IEC Guide 51.

Common sumps or catchment tanks, if required, for several transformers shall be arranged so that a fire in one transformer cannot spread to another.

The same applies to individual sumps which are connected to the catchment tanks of other transformers; gravel layers or pipes filled with fluid can, for example, be used for this purpose. Arrangements which tend to minimize the fire hazard of the escaped fluid are preferred.

Re. 8.6.2.1 Outdoor installations

The layout of an outdoor installation shall be such that burning of a transformer with a liquid volume of more than 1 000 l will not cause a fire hazard to other transformers or objects. For this purpose adequate clearances, G, shall necessary. Guide values are given in table 3. Where transformers with a liquid volume below 1 000 l are installed near combustible walls, special fire precautions may be necessary depending on the nature and the use of the building.

If it is not possible to allow for adequate clearance as indicated in table 3, fire-resistant separating walls with the following dimensions shall be provided:

- a. between transformers (see figure 6) separating walls. For example EI 60 in accordance with the Official Journal of the European Community, No. C 62/23:
 - height: top of the expansion chamber (if any), otherwise the top of the transformer tank;
 - length: width or length of the sump (in the case of a dry-type transformer, the width or length of the transformer, depending upon the direction of the transformer);
- b. between transformers and buildings (see figure 7) separating walls. For example EI 60; if additional fire separating wall is not provided, fire rating of the building wall should be increased, for example REI 90 in accordance with the Official Journal of the European Community C 62/23.

Re. 8.6.2.2 Indoor installations in electrical power systems

Minimum requirements for the installation of indoor transformers are given in table 4.

Table 3 – Guide values for outdoor transformer clearances

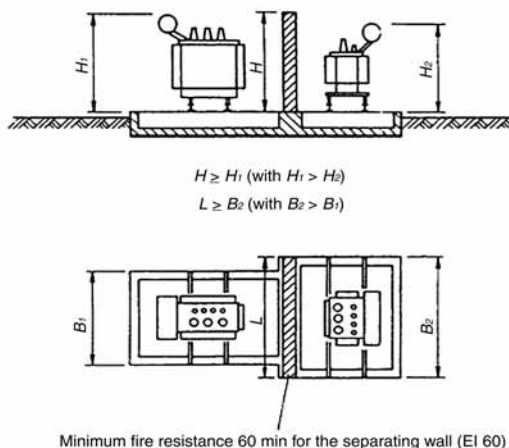
Transformer type	Liquid volume L	Clearance G to	
		other transformers or non-combustible building surface m	combustible building surface m
Oil insulated transformers (O)	1 000 <.....< 2 000	3	7,6
	2 000 ≤.....< 20 000	5	10
	20 000 ≤.....< 45 000	10	20
	≥ 45 000	15,2	30,5
Less flammable liquid insulated transformers (K) without enhanced protection	1 000 <.....< 3 800	15,2	30,5
	≥ 3 800	4,6	15,2
Less flammable liquid insulated transformers (K) with enhanced protection	Clearance G to building surface or adjacent transformers		
	Horizontal m	Vertical m	
	0,9	1,5	
Dry type transformers (A)	Fire behaviour class	Clearance G to building surface or adjacent transformers	
		Horizontal m	Vertical m
	F0	1,5	3,0
	F1 / F2	None	None
NOTE Enhanced protection means – tank rupture strength; – tank pressure relief; – low current fault protection; – high current fault protection. For an example of enhanced protection, see Factory Mutual Global standard 3990, or equivalent.			

If automatically activated fire extinguishing equipment is installed, the clearance G can be reduced.

Table 4 – Minimum requirements for the installation of indoor transformers

Transformer type	Liquid volume l	Safeguards
Oil insulated transformers (O)	$\leq 1\,000$	EI 60 respectively REI 60
	$> 1\,000$	EI 90 respectively REI 90 or EI 60 respectively REI 60 and automatic sprinkler protection
Less flammable liquid insulated transformers (K) without enhanced protection		EI 60 respectively REI 60 or automatic sprinkler protection
Less flammable liquid insulated transformers (K) with enhanced protection	≤ 10 MVA and $U_m \leq 38$ kV	EI 60 respectively REI 60 or separation distances 1,5 m horizontally and 3,0 m vertically
Dry-type transformer (A)	Fire behaviour class	
	F0	EI 60 respectively REI 60 or separation distances 0,9 m horizontally and 1,5 m vertically
	F1 / F2	Non combustible walls
NOTE 1 REI represents bearing system (wall) whereas EI represents non-load bearing system (wall) where R is the load bearing capacity, E is the fire integrity, I is the thermal insulation and 60/90 refers to time in minutes. NOTE 2 Enhanced protection means – tank rupture strength; – tank pressure relief; – low current fault protection; – high current fault protection. For an example of enhanced protection, see Factory Mutual Global standard 3990 or equivalent.		

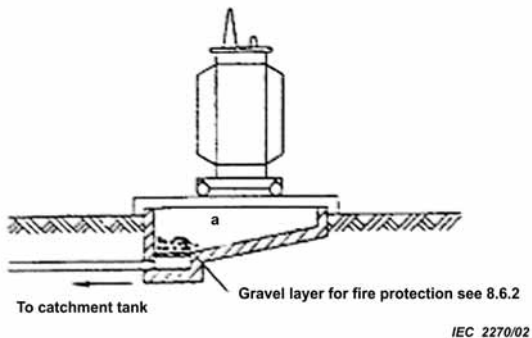
Doors shall have a fire resistance of at least 60 min. Doors which open to the outside are adequate if they are of fire-retardant material and construction. Ventilation openings necessary for the operation of the transformers are permitted. When designing the openings, the possible escape of hot gases shall be considered.



IEC 2267/02

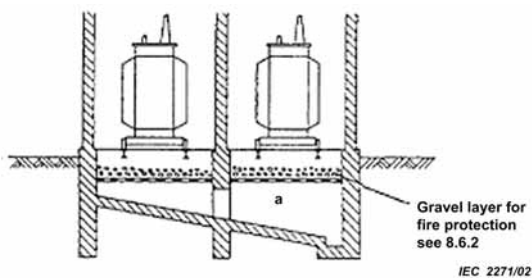
Figure 6 – Separating walls between transformers

^a The wall in this area shall be designed to avoid spread of fire.



^a Containment: minimum 20% of the fluid from the transformer

Figure 9 – Sump with separated catchment tank

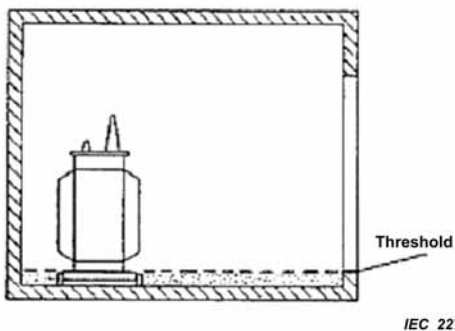


NOTE In addition, the water from fire extinguishing installation (if any) should be considered

^a Containment outdoor: the entire quantity of fluid of the largest transformer plus rain

Containment indoor: the entire quantity of fluid of the largest transformer

Figure 10 – Sump with integrated common catchment tank



NOTE The dotted area denotes the volume of the entire quantity of insulating fluid of the transformer spilled on the floor

Figure11 – Example for small transformer without gravel layer and catchment tank

Re. 9 PROTECTION, CONTROL AND AUXILIARY SYSTEMS

Re. 9.1 Monitoring and control systems

Monitoring, protection, regulating and control devices shall be provided, as necessary, for the correct and safe functioning of the equipment.

Automatic devices, designed to offer selectivity and quick operation, shall provide protection against the effects of unacceptable overload and internal and external faults appropriate to the size and significance of installation.

Equipment shall comply with the severity class (see IEC 60255) corresponding to the part of the installation in which it is located.

Facilities shall be provided for isolating the control circuit of each primary switching equipment or each switchgear bay in order to allow maintenance of high voltage equipment to be performed safely.

Provision shall be made to allow for repair, maintenance, and/or testing to be carried out on protection and control devices without any danger to personnel or the equipment.

Control circuits and signalling circuits shall, preferably, be functionally separated. Tripping signals shall be displayed on the protection panel if it exists.

Alarm and fault-indicating equipment shall clearly indicate danger and fault conditions; several signals can be combined as a common signal to be transmitted to a remote control point.

The control equipment and system, including cables and cords, shall be designed and installed to minimize the possibility of damage to the connected equipment due to electromagnetic interference. Basic rules are given in 9.5.

The control equipment and system, including cables and cords, shall be designed and installed in such a way that they minimize the danger from operating failure, inadvertent operation or incorrect information. In meeting this requirement, influences such as voltage dips, supply failure, insulation faults and electromagnetic interference effects shall be taken into account.

Re. 10 EARTHING SYSTEMS

Re. 10.1 General

This clause provides the criteria for design, installation, testing and maintenance of an earthing system such that it operates under all conditions and ensures the safety of human life in any place to which persons have legitimate access. It also provides the criteria to ensure that the integrity of equipment connected and in proximity to the earthing system is maintained.

Re. 10.2 Fundamental requirements

Re. 10.2.1 Safety criteria

The hazard to human beings is that a current will flow through the region of the heart which is sufficient to cause ventricular fibrillation. The current limit, for power-frequency purposes, should be derived from IEC 60479-1 (curve C1). For substation design, this curve needs to be translated into voltage limits for comparison with the calculated step and touch voltages taking into account the impedance present in the body current path. Annex B shows curves of typical voltage limits. The voltage limits shall take into account the following factors:

- proportion of current flowing through the region of the heart;
- body impedance along the current path
(based on the 5 % values of table 1 of IEC 60479-1);
- resistance between the body contact points and return paths
(e.g. remote earth, earth electrode);
- fault duration;
- fault current magnitude.

It must also be recognized that fault occurrence, fault current magnitude, fault duration and presence of human beings are probabilistic in nature.

(normative)

Values of rated insulation levels and minimum clearances based on current practice in some countries

Table A.1 – Values of rated insulation levels and minimum clearances in air for $1 \text{ kV} < U_m \leq 245 \text{ kV}$ for highest voltages for equipment U_m not standardized by the IEC based on current practice in some countries

Voltage range	Nominal voltage of system	Highest voltage for equipment	Rated short-duration power-frequency withstand voltage	Rated lightning impulse withstand voltage ^a	Minimum phase-to-earth and phase-to-phase clearance, <i>N</i> ^b		
	<i>U_n</i> r.m.s.	<i>U_m</i> r.m.s.	r.m.s.	1,2/50 μs (peak value)	Indoor installations	Outdoor installations	
	kV	kV	kV	kV	mm	mm	
I		2,75	15	30 45 60	60 70 90	120 120 120	
		4,76	19	60	90	120	
		5,5	19	45 60 75	70 90 120	120 120 120	
		8,25	27	60 75 95	90 120 160	120 150 160	
		8,25	26 35	75 95	120 160	150 160	
		15	35 50	95 110	160 180	160 180	
		15,5	35	75 85 110	120 150 180	150 160 180	
	15	17,5	38	110 125	180 220		
	22 (20)	24	50	150	280		
	22	25	50	95 125 150	190 210	290	
		25,8	50 70	125 150	220 280		
		27	50	95 125 150	160 220 280		
	^a	The rated lightning impulse is applicable phase-to-phase and phase-to-earth.					
	^b	For rod-structure					

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