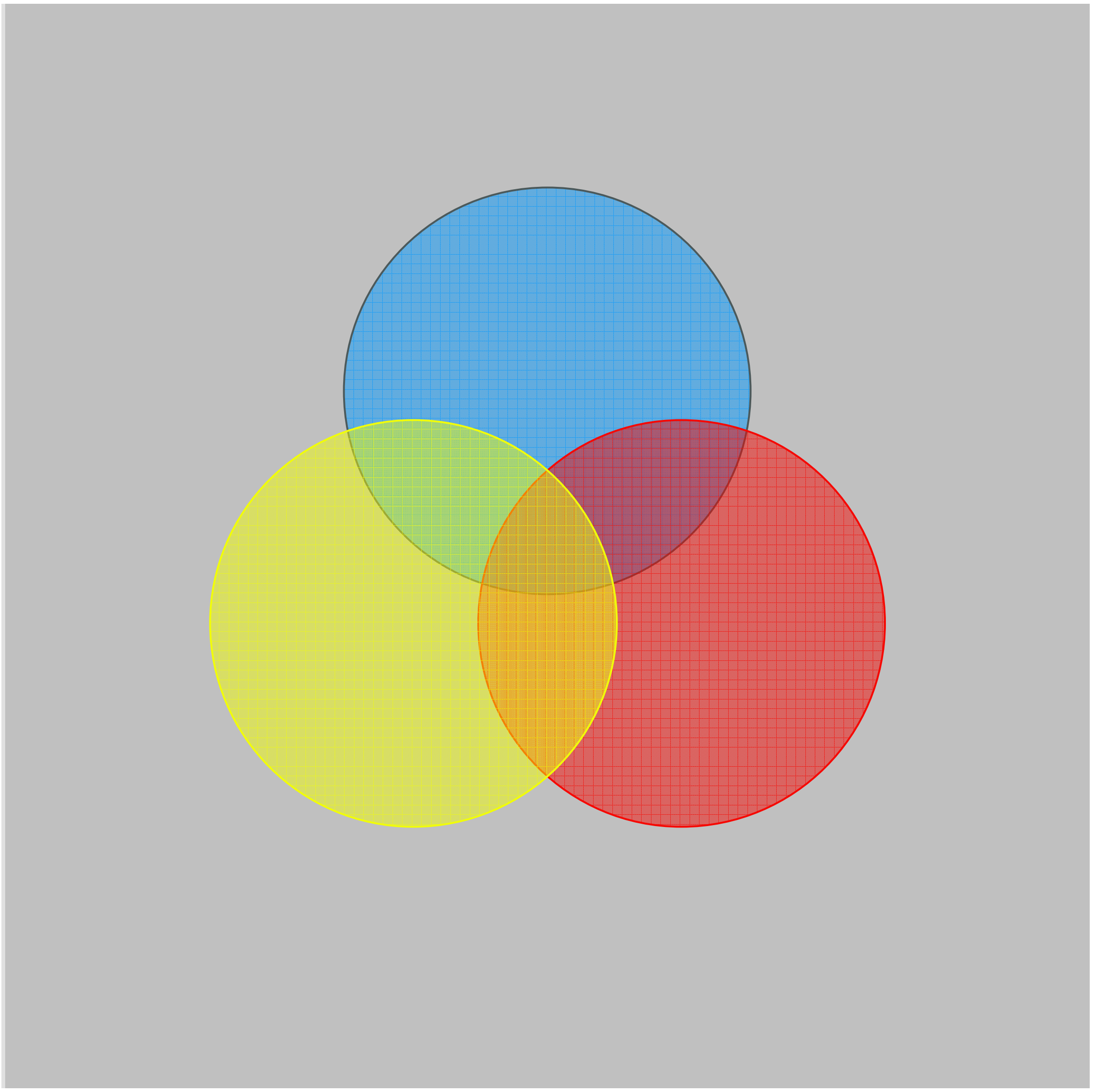
POWER TRANSFORMERS

IN AND OUT



MANSOOR

CHAPTERS AND CONTENTS

Chapter-1

1 INTRODUCTION

1.1 Brief Overview of Transformers

Power generation transmission and distribution throughout the world is through A.C system and the voltages are different at each level of the network.

A transformer is a device that transfers energy from one AC system to another. A transformer can accept energy at one voltage and deliver it at another voltage. This permits electrical energy to be generated at relatively low voltages and transmitted at high voltages and low currents, thus reducing line losses, and again it is stepped down from higher to lower levels to be used at safe voltages. Power transformers are necessary for increasing the voltage from generation to transmission system and then decreasing from transmission to sub-transmission and distribution system.

The total transformer capacity is usually 8 to 10 times the total generating capacity, therefore transformers are a very important apparatus in the electrical network, it is a capital equipment with a life expectancy of several decades and care should be taken about selection and ratings for which a good understanding of the basics and principles of operation is essential.
The KVA (Power) rating of a power transformer covers a wide range between 5 KVA to 750 MVA. Very big transformers are installed in generating stations and HVDC converter stations very small transformers are used in low voltage and electronic circuits. The KVA rating of the transformer depends on the load connected which is normally on the secondary winding

An analogy

The transformer may be considered as a simple two-wheel 'gearbox' for electrical voltage and current. The primary winding is analogous to the input shaft and the secondary winding to the output shaft. In this comparison, current is equivalent to shaft speed, voltage to shaft torque. In a gearbox, mechanical power (speed multiplied by torque) is constant (neglecting losses) and is equivalent to electrical power (voltage multiplied by current) which is also constant.

The gear ratio is equivalent to the transformer step-up or step-down ratio. A step-up transformer acts analogously to a reduction gear (in which mechanical power is transferred from a small, rapidly rotating gear to a large, slowly rotating gear): it trades current (speed) for voltage (torque), by transferring power from a primary coil to a secondary coil having more turns. A step-down transformer acts analogously to a multiplier gear (in which mechanical power is transferred from a large gear to a small gear): it trades voltage (torque) for current (speed), by transferring power from a primary coil to a secondary coil having fewer turns.

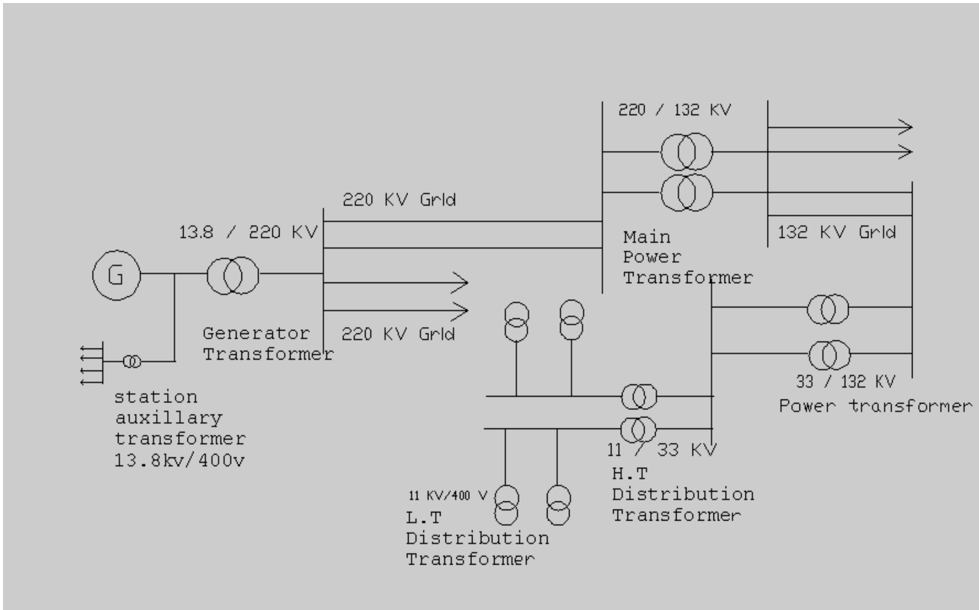


Fig 1.1

Diagram showing the location of different power transformers from generation to the L.T (domestic) power network (circuit breakers and other equipment are not shown)

A transformer is an electrical device that transfers energy from one circuit to another purely by magnetic coupling. Relative motion of the parts of the transformer is not required.

1.2 Flux coupling laws

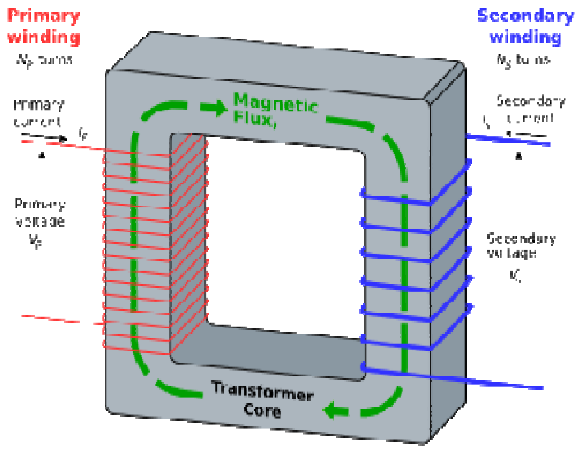


Fig 1.2

An idealized step-down transformer showing resultant flux in the core

A simple transformer consists of two electrical conductors called the primary winding and the secondary winding. If a time-varying voltage v_P (Sinusoidal) is applied to the primary winding of turns, a current will flow in it producing a magneto motive force (MMF). Just as an electromotive force (EMF) drives current around an electric circuit, so MMF drives magnetic flux through a magnetic circuit. The primary MMF produces a varying magnetic flux Φ_P in the core (shaded grey), and induces a back electromotive force (EMF) in opposition to. In accordance with Faraday's Law, the voltage induced across the primary winding is proportional to the rate of change of flux:

$$v_P = N_P \frac{d\Phi_P}{dt}$$

Similarly, the voltage induced across the secondary winding is:

$$v_S = N_S \frac{d\Phi_S}{dt}$$

With perfect flux coupling, the flux in the secondary winding will be equal to that in the primary winding, and so we can equate Φ_P and Φ_S. It thus follows that

$$\frac{v_P}{v_S} = \frac{N_P}{N_S}.$$

Hence in an ideal transformer, the ratio of the primary and secondary voltages is equal to the ratio of the number of turns in their windings, or alternatively, the voltage per turn is the same for both windings. This leads to the most common use of the transformer: to convert electrical energy at one voltage to energy at a different voltage by means of windings with different numbers of turns.

The EMF in the secondary winding, if connected to an electrical circuit, will cause current to flow in the secondary circuit. The MMF produced by current in the secondary opposes the MMF of the primary and so tends to cancel the flux in the core. Since the reduced flux reduces the EMF induced in the

primary winding, increased current flows in the primary circuit. The resulting increase in MMF due to the primary current offsets the effect of the opposing secondary MMF. In this way, the electrical energy fed into the primary winding is delivered to the secondary winding.
Neglecting losses, for a given level of power transferred through a transformer, current in the secondary circuit is inversely proportional to the ratio of secondary voltage to primary voltage. For example, suppose a power of 50 watts is supplied to a resistive load from a transformer with a turns ratio of 25:2.

P = E×I (power = electromotive force× current)
50 W = 2 V × 25 A in the primary circuit
Now with transformer change:
50 W = 2 A × 25 V in the secondary circuit.

The high-current low-voltage windings have fewer turns of wire. The high-voltage, low-current windings have more turns of wire.
Since a DC voltage source would not give a time-varying flux in the core, no back EMF would be generated and so current flow into the transformer would be unlimited. In practice, the series resistance of the winding limits the amount of current that can flow, until the transformer either reaches thermal equilibrium or is destroyed.

The Universal EMF equation

If the flux in the core is sinusoidal, the relationship for either winding between its number of turns, voltage, magnetic flux density and core cross-sectional area is given by the universal emf equation:

E=4.44 *f* n a b

Where E is the sinusoidal root mean square (RMS) voltage of the winding, ***f*** is the frequency in hertz, n is the number of turns of wire, a is the area of the core (square units) and b is magnetic flux density in webers per square unit. The value 4.44 collects a number of constants required by the system of units.

Invention

Those credited with the invention of the transformer include:

- Michael Faraday, who invented an 'induction ring' on August 29, 1831. This was the first transformer, although Faraday used it only to demonstrate the principle of electromagnetic induction and did not foresee the use to which it would eventually be put.
- Lucien Gaulard and John Dixon Gibbs, who first exhibited a device called a 'secondary generator' in London in 1881 and then sold the idea to American company Westinghouse. This may have been the first practical power transformer, but was not the first transformer of any kind. They also exhibited the invention in Turin in 1884, where it was adopted for an electric lighting system. Their early devices used an open iron core, which was later abandoned in favour of a more efficient circular core with a closed magnetic path.
- William Stanley, an engineer for Westinghouse, who built the first practical device in 1885 after George Westinghouse bought Gaulard and Gibbs' patents. The core was made from interlocking E-shaped iron plates. This design was first used commercially in 1886.
- Hungarian engineers Ottó Bláthy, Miksa Déri and Károly Zipernowsky at the Ganz company in Budapest in 1885, who created the efficient "ZBD" model based on the design by Gaulard and Gibbs.
- Nikola Tesla in 1891 invented the Tesla coil, which is a high-voltage, air-core, dual-tuned resonant transformer for generating very high voltages at high frequency.

Types of transformers

1. Power transformers (Step-up and Step-down)

2. Instrument Transformers (Current and voltage)
3. HVDC Converter Transformers
4. Reactors (Series and Shunt)
5. Isolation Transformers
6. Variable auto-transformers
7. Signal transformers

Power Transformers are used for stepping up and down of generation and in distribution of power in a network, these are generally fully loaded transformers.
Instrument Transformers are used for measurement, and protection of HV electrical networks from faults
HVDC converter Transformers are used as an impedance load and isolation from the DC system, these are generally at a similar voltage level 400 / 500 KV AC for where the 500 KV AC system is fed to the AC to DC converter system
Reactors are used for compensation of reactive power in the network, two types of reactors used are 1) Series and 2) Shunt these are similar in principle, operation and construction as transformers.
Isolation Transformers are used to isolate two circuits physically for safety and security.
Variable auto-transformers are used when a variable voltage (hence current) is required especially for testing and calibration.
Signal transformers are used in electronic circuits for electrically connecting different regions are circuits and physical isolation.

1.3 Transformer ratings

When a transformer is to be used in a circuit, more than just the turns ratio must be considered. The voltage, current, and power-handling capabilities of the primary and secondary windings must also be considered.
The maximum voltage that can safely be applied to any winding is determined by the type and thickness of the insulation used. When a better (and thicker) insulation is used between the windings, a higher maximum voltage can be applied to the windings.
The maximum current that can be carried by a transformer winding is determined by the diameter of the wire used for the winding. If current is excessive in a winding, a higher than ordinary amount of power will be dissipated by the winding in the form of heat. This heat may be sufficiently high to cause the insulation around the wire to break down. If this happens, the transformer may be permanently damaged.
The power-handling capacity of a transformer is dependent upon its ability to dissipate heat. If the heat can safely be removed, the power-handling capacity of the transformer can be increased. This is sometimes accomplished by immersing the transformer in oil, or by the use of cooling fins. The power-handling capacity of a transformer is measured in either the volt-ampere unit or the watt unit.

If the frequency applied to a transformer is increased, the inductive reactance of the windings is increased, causing a greater ac voltage drop across the windings and a lesser voltage drop across the load. However, an increase in the frequency applied to a transformer should not damage it. But, if the frequency applied to the transformer is decreased, the reactance of the windings is decreased and the current through the transformer winding is increased. If the decrease in frequency is enough, the resulting increase in current will damage the transformer. For this reason a transformer may be used at frequencies above its normal operating frequency, but not below that frequency.

Apparent Power Equation or KVA rating of a Single phase transformer

KVA = Vp * Ip where Vp is phase rms voltage in KV and Ip is rms current in Amps.

Apparent Power Equation or KVA rating of a three phase transformer

KVA = $\sqrt{3}$ * Vp * Ip where Vp is line to line rms voltage in KV and Ip is rms line current in Amps.

Construction

A transformer usually has:

- Two or more insulated windings, to carry current
- A core, in which the mutual magnetic field couples the windings.

In transformers designed to operate at low frequencies, the windings are usually formed around an iron or steel core. This helps to confine the magnetic field within the transformer and increase its efficiency, although the presence of the core causes energy losses. Transformers made to operate at high frequencies may use other lower loss materials, or may use an air core.

Core Construction

Power transformers are further classified by the exact arrangement of the core and windings as "shell type", "core type" and also by the number of "limbs" that carry the flux (3, 4 or 5 for a 3-phase transformer).
Core type shape is mostly used in three-phase distribution transformers. The window height Ha depends on the coil height and the core area Ar depends on the rated power S n.

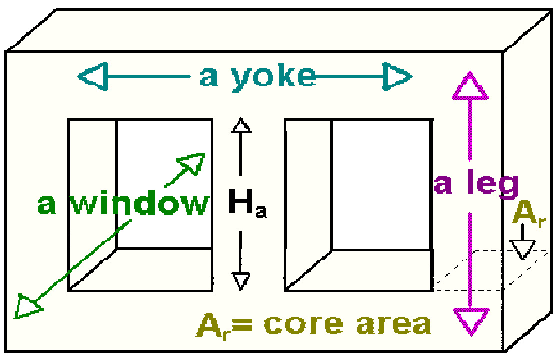


Fig 1.3

There are five main groups of magnetically soft alloys classified primarily by the chief constituents of the metal.
low-carbon steel
silicon steel
nickel-iron
cobalt-nickel-iron
cobalt-iron

Steel cores
Transformers often have silicon steel cores to channel the magnetic field. This keeps the field more concentrated around the wires, so that the transformer is more compact. The core of a power

transformer must be designed so that it does not reach magnetic saturation. Carefully designed gaps are sometimes placed in the magnetic path to help prevent saturation. Practical transformer cores are always made of many stamped pieces of thin steel. The high resistance between layers reduces eddy currents in the cores that waste power by heating the core. These are common in power and audio circuits. A typical laminated core is made from E-shaped and I-shaped pieces, leading to the name "EI transformer". One problem with a steel core is that it may retain a static magnetic field when power is removed. When power is then reapplied, the residual field may cause the core to temporarily saturate. This can be a significant problem in transformers of more than a few hundred watts output, since the higher inrush current can cause mains fuses to blow unless current-limiting circuitry is added. More seriously, inrush currents can physically deform and damage the primary windings of large power transformers.

Solid cores

In higher frequency circuits such as switch-mode power supplies, powdered iron cores are sometimes used. These materials combine a high magnetic permeability with a high material resistivity. At even higher frequencies (radio frequencies typically) other types of core made of nonconductive magnetic materials, such as various ceramic materials called ferrites are common. Some transformers in radio-frequency circuits have adjustable cores which allow tuning of the coupling circuit.

Air cores

High-frequency transformers also use air cores. These eliminate the loss due to hysteresis in the core material. Such transformers maintain high coupling efficiency (low stray field loss) by overlapping the primary and secondary windings.

Toroidal cores

Toroidal transformers are built around a ring-shaped core, which is made from a long strip of silicon steel wound into a coil. This construction ensures that all the grain boundaries are pointing in the optimum direction, making the transformer more efficient by reducing the core's reluctance, and eliminates the air gaps inherent in the construction of an EI core. The cross-section of the ring is usually square or rectangular, but more expensive cores with circular cross-sections are also available. The primary and secondary coils are wound concentrically to cover the entire surface of the core. This minimises the length of wire needed, and also provides screening to prevent the core's magnetic field from generating electromagnetic interference.

Toroidal cores for use at frequencies up to a few tens of kilohertz is made of ferrite material to reduce losses. Such transformers are used in switch-mode power supplies.

Windings

Power transformers are wound with wire, copper or aluminum rectangular conductors, or strip conductors for very heavy currents. Very large power transformers will also have multiple strands in the winding, to reduce skin effect (The skin effect is the tendency of an alternating electric current to distribute itself within a conductor so that the current density near the surface of the conductor is greater than that at its core).

Windings on both primary and secondary of a power transformer may have taps to allow adjustment of the voltage ratio; taps may be connected to automatic on-load tapchanger switchgear for voltage regulation of distribution circuits.

1.4 Understand the terminology

E-I lamination
A flat transformer steel lamination composed of pairs of E-shaped and I shaped pieces. The middle projection or tongue of the E is placed through the center of a coil of wire, and the I placed at the end like this" EI" so the iron forms a complete magnetic path through the center and around the outside of the coil.

Scrapless lamination
An E-I lamination with proportions such that two E's and two I's are stamped from a rectangle of iron with no waste left over. This is the least expensive shape for transformer iron, and is the standard for the industry for non-special purpose transformers. The proportions are special, obviously. The I's are stamped from the open areas of two end-facing E's. The middle part, or tongue, of each E is twice as wide as the two outer legs, and the empty area stamped out of the E (which forms the I) is half as long as the E is high from top to bottom. As you can see, since the proportions are pre-determined, you can specify any one dimension and all the rest are determined. E-I laminations are usually named by the tongue width: EI100 has a tongue that is 1.00 inches wide. EI150 is 1.5" wide, etc.

Primary inductance
If you connect only the primary wires of a transformer, and measure the inductance, no energy leaves through any secondary windings, so the thing looks like (and is!) just an inductor. The amount of inductance you measure is the primary inductance. The primary inductance is a consequence of the iron and air in the magnetic field path, and is non-linear - you would measure somewhat different values under different conditions.

Secondary inductance
Likewise, what you measure if you connect a measurement instrument only to the secondaries.

L**eakage inductance**
Leakage inductance is inductance that results from the parts of the primary's magnetic field that does not link the secondary. This is an inductance from which the secondary can never draw energy, and represents a loss of effectiveness in the transformer. If you short the secondary winding and then measure the "primary" inductance, you will measure the leakage inductance, which appears to be in series with the primary winding.

Core loss
The iron in the core is itself conductive, and the magnetic field in it induces currents. These currents cause the loss of energy, and this comes out as heat. The core loss represents a price you have to pay to use a transformer. Core loss is strongly related to frequency, increasing linearly as the frequency goes up.

Eddy current
Eddy currents are the currents induced in conductors in a magnetic field - such as the iron core. The inside of a conductor looks like a shorted transformer turn to the magnetic field, so the currents can be large, and can cause substantial heating, as in the core losses.

Copper loss

Copper is not a perfect conductor. Current moving through copper causes the copper to heat up as it moves through the resistance of the wire.

Winding window

This is the area of a core available for winding wires into.

Margins

Space left at the end of a coil former where no copper windings are placed. This keeps the copper wire from going out to the very edges of the coil former, and improves the voltage isolation between layers and windings.

Window fill

The amount of the winding window that is filled up with copper wires, insulation, etc. Usually expressed as a percent of the winding window area.

Interlayer insulation

After winding a neat layer of wire on a coil, you put a thin layer of insulating paper, plastic film, etc. over it. This is interlayer insulation. It helps keep the insulation of the wires from breaking down from the stress of the voltage difference between layers, and mechanically helps form a neat, solid coil.

B

Magnetic field intensity, or "flux density"; sometimes measured in flux lines, Gauss or kiloGauss, or Teslas depending on the measurement system you use. Most transformer iron saturates around 14 to 20 kGauss. Ceramic materials saturate at around 3-4kGauss.

H

Coercive force. This is what "forces" the magnetic field into being. It's usually measured in Ampere-Turns per unit of magnetic circuit length, often ampere-turns per meter.

B-H curve

Pretty simply, the graph of B versus the causative H. When there is a large slope of B versus H, the permeability of the material is high.

Saturation

At saturation, the permeability falls off, as more H cannot cause higher B.

Insulation class

Transformer insulation is rated for certain amounts of temperature rise. Materials which withstand temperatures under 105C are Class A. Class B materials withstand higher termperatures, and other letters even higher temperatures. Class A insulation is the most common for output transformers, as no great temperature rise (by power transformer standards at least) are encountered. This "class" is not related to the bias class of the amplifier at all, they just happened to use the same words.

Stack

How much iron is put inside the coils of wire making up the windings of the transformer. The lamination size determines the width of the tongue, the stack height determines the height, and the width times the height is the core area, which is a key determiner of the power handling capability of the transformer. All other things being equal, more stack height means either a greater inductance for a given number of turns, or a fewer number of turns for the same inductance. This is one means of juggling wire sizes and window fill.

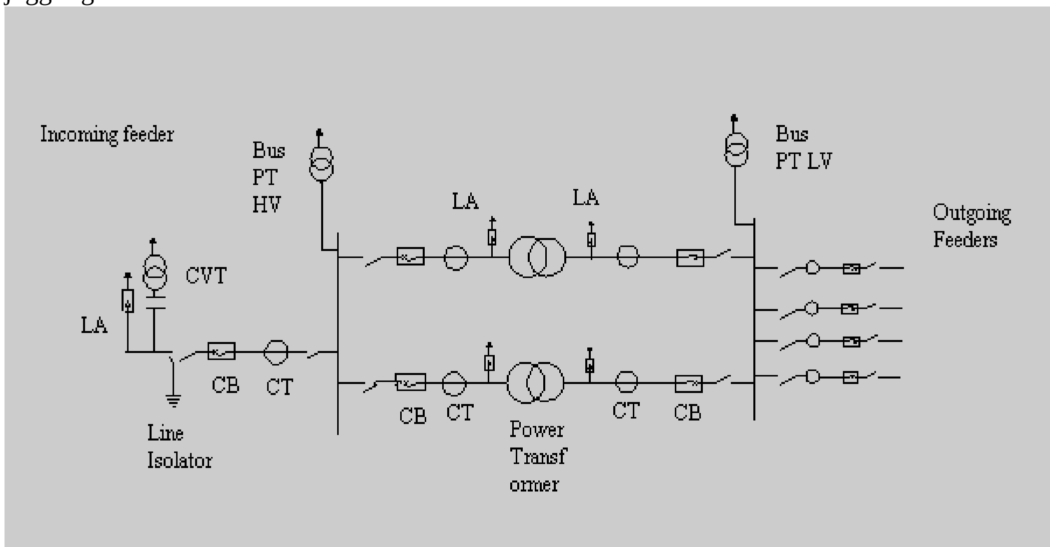


Fig 1.4

Equipment associated with a power transformer in a sub-station with one incoming (HV) and four outgoing (LV) feeders (transmission lines)

Where LA – Lighting (Surge arrestor)

CT- Current Transformer

PT – Voltage Transformer

CB – Circuit Breaker

TYPE TESTS

- Temperature rise
- Short circuit
- Lightning Impulse
- Sound level
- Energy Performance
- Switching Surge Impulse
- Zero Sequence Impedance

ROUTINE TESTS PERFORMED ON ALL TRANSFORMERS:

- Ratio and Polarity
- Power Factor
- Winding Resistance
- No-Load Loss and Excitation Current
- Load Loss and Impedance

- C.T. Current, Ratio and Polarity
- Standard Impulse Test (Class I I Transformers)
- Quality Control Impulse Test (Class I Transformers)
- Applied Potential
- Quality Control Induced Voltage Test with Corona Detection (Class I Transformers)
- Control Functions and Wiring
- Dissolved Gas Analysis
- Dew Point

Chapter-2

2 MAGNETISM AND MAGNETIC FIELDS

2.1 Magnetism: quantities, units and relationships

Magnetic quantities in the SI
Table 2.1

Quantity name	Quantity symbol	Quantity name	Quantity symbol
coercivity	Hc	core factor	Σl/A
effective area	Ae	effective length	le
effective permeability	μe	flux linkage	λ
induced voltage	e	inductance	L
inductance factor	Al	initial permeability	μi
intensity of magnetization	I	magnetic field strength	H
magnetic flux	Φ	magnetic flux density	B
magnetic mass susceptibility	χρ	magnetic moment	m
magnetic polarization	J	magnetic susceptibility	χ
magnetization	M	magnetomotive force	Fm
permeability	μ	permeability of vacuum	μ0
relative permeability	μr	reluctance	Rm
remnance	Br		

An Example Toroid Core

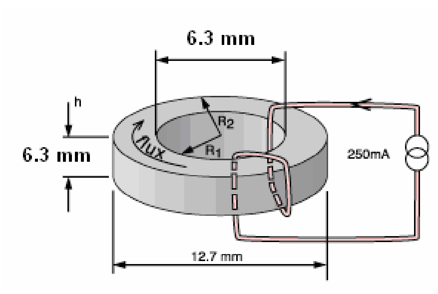


Figure 2.1 torroid core

As a concrete example for the calculations throughout this page we consider the 'recommended' toroid, or ring core, Manufacturers use toroids to derive material characteristics because there is no gap, even a residual one. Such tests are done using fully wound cores rather than just the two turns here; but, providing the permeability is high, then the error will be small.

Table 2.2

Parameter	Symbol	Value
Effective magnetic path length	l_e	27.6×10-3 m
Effective core area	A_e	19.4×10-6 m2
Relative permeability	μ_r	2490
Inductance factor	A_l	2200 nH
saturation flux density	B_{sat}	360 mT

Let's take a worked example to find the inductance for the winding shown with just two turns (N=2).

$\Sigma l/A = le / Ae = 27.6\times10^{-3} / 19.4\times10^{-6} = 1420\ m^{-1}$

$\mu = \mu 0 \times \mu r = 1.257\times10^{-6} \times 2490 = 3.13\times10^{-3}\ Hm^{-1}$

$Rm = (\Sigma l/A) / \mu = 1420 / 3.13\times10^{-3} = 4.55\times10^{5}\ \ A\text{-}t\ Wb^{-1}$

$$Al = 10^{9} / Rm = 10^{9} / 4.55\times10^{5} = 2200\ nH\ \text{per turn}^{2}$$

$$L = Al \times N^{2} = 2200 \times 10^{-9} \times 2^{2} = 8.8\ \mu H$$

Core Factor :Core Factor in the SI

Table 2.3

Quantity name	core factor or geometric core constant
Quantity symbol	Σl/A
Unit name	per metre
Unit symbols	m-1

The idea of core factor is, apart from adding to the jargon :-(, to encapsulate in one figure the contribution to core reluctance made by the size and shape of the core. It is usually quoted in the data sheet but it is calculated as -

$\Sigma l/A = le / Ae\ \ m^{-1}$

So for our example toroid we find -

$\Sigma l/A = 27.6\times10^{-3} / 19.4\times10^{-6} = 1420\ \ m^{-1}$

Core factors are often specified in millimetres^{-1}. You should then multiply by 1000 before using them in the formula for reluctance.

Effective Area

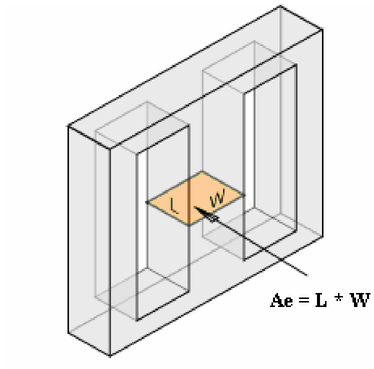


Figure 2.2 Effective area

The 'effective area' of a core represents the cross sectional area of one of its limbs. Usually this corresponds closely to the physical dimensions of the core but because flux may not be distributed completely evenly the manufacturer will specify a value for A_e which reflects this.

The need for the core area arises when you want to relate the flux density in the core (limited by the material type) to the total flux it carries -

$A_e = \Phi / B$

In the example toroid the area could be determined approximately as the product of the core height and the difference between the major and minor radii -

$A_e = 6.3 \times ((12.7 - 6.3) / 2) = 20.2 \quad mm^2$

However, because the flux concentrates where the path length is shorter it is better to use the value stated by the manufacturer - 19.4 mm^2. For the simple toroidal shape A_e is calculated as

$A_e = h \times \ln^2(R_2/R_1) / (1/R_1 - 1/R_2) \quad m^2$

This assumes square edges to the toroid; real ones are often rounded.

There is a slight twist to the question of area: the manufacturer's value for A_e will give give the correct results when used to compute the core reluctance but it may not be perfect for computing the saturation flux (which depends upon the narrowest part of the core or A_{min}). In a well designed core A_{min} won't be very different from A_e, but keep it in mind.

Note :Effective area is usually quoted in millimetres squared. Many formulae in data books implicitly assume that a numerical value in mm^2 be used. Other books, and these notes, assume metres squared.

Effective Length

Effective Length in the SI

Table 2.4

Quantity name	effective length
Quantity symbol	l_e
Unit name	metre
Unit symbols	m

The 'effective length' of a core is a measure of the distance which flux lines travel in making a complete circuit of it. Usually this corresponds closely to the physical dimensions of the core but because flux has a tendency to concentrate on the inside corners of the path the manufacturer will specify a value for l_e which reflects this.

In the toroid example the path length could be determined approximately as -

$l_e = \pi \times (12.7 + 6.3) / 2 = 29.8$ mm

However, because the flux concentrates where the path length is shorter it is better to use the value stated by the manufacturer - 27.6 mm. For a simple toroidal shape l_e is calculated as

$l_e = 2\pi \times \ln(R_2 / R_1)/ (1 / R_1 - 1 / R_2)$

Another common core type, the EE, is shown in Fig: is shown in Fig: 2.3

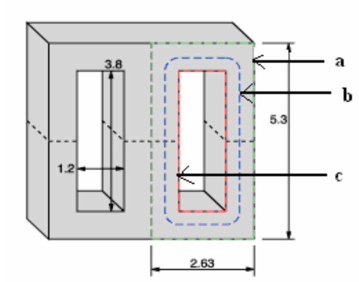


Figure 2.3 Flux paths

The (c) line represents the shortest path which a flux line could take to go round the core. The (a) line is the longest. Shown in (b) is a path whose length is that of the short path plus four sectors whose radius is sufficient to take the path mid-way down the limbs.

$l_e = 2(3.8 + 1.2) + \pi((2.63 - 1.2) / 2)$

= 12.25 mm This is all a bit approximate; but bear in mind that since manufacturing tolerances on permeability are often 25% there isn't much point in being more exact.

Table 2.5

Quantity name	magnetomotive force
Quantity symbol	F_m, η or $\Im$
Unit name	ampere
Unit symbol	A

Note: Effective length is usually quoted in millimeters. Many formulae in data books implicitly assume that a numerical value in mm be used. Other books, and these notes, assume metres.

Table 2.6

Comparison with with the Electric units		
Quantity	**Unit**	**Formula**
Magnetomotive force	amperes	F_m = H × le
Electromotive force	volts	V = E (Electric field strength) × l (distance)

MMF can be thought of as the magnetic equivalent of electromotive force. You can calculate it as -

$F_m = I \times N$ ampere turns
The units of MMF are often stated as *ampere turns* (A-t) because of this. In the example toroid core-
$F_m = 0.25 \times 2 = 0.5$ ampere turns

Differentiate magnetomotive force with magnetic field strength (magnetizing force). As an analogy think of the plates of a capacitor, with a certain *electromotive* force (EMF) between them. How high the electric field strength is will depend on the distance between the plates. Similarly, the magnetic field strength in a transformer core depends not just on the MMF but also on the distance that the flux must travel round it.

A magnetic field represents stored energy and $F_m = 2\ W / \Phi$

where W is the energy in joules. You can also relate mmf to the total flux going through part of a magnetic circuit whose reluctance you know.

$F_m = \Phi \times Rm$ Rowland's Law
There is a clear analogy here with an electric circuit and Ohm's Law, V = I × R. Magnetic Field StrengthMagnetic Field Strength in the SI

Table 2.7

Quantity name	magnetic field strength
Quantity symbol	H
Unit name	ampere per metre
Unit symbols	A m-1

Whenever current flows it is always accompanied by a magnetic field. Scientists talk of the field as being due to 'moving electric charges' - a reasonable description of electrons flowing along a wire.

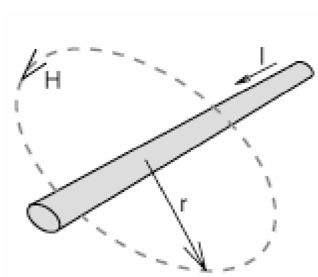


Figure 2.3 Magnetic field
The strength, or intensity, of this field surrounding a straight wire is given by
$H = I / (2 \pi r)$ --------

where r, the distance from the wire, is small in comparison with the length of the wire. The situation for short wires is described by the Biot-Savart equation.

By the way, don't confuse the speed of the charges (such as electrons) with the speed of a signal travelling down the wire they are in. Think of the signal as being the boundary between those electrons that have started to move and those that have yet to get going. The boundary might move close to the speed of light ($3x10^8$ m s^{-1}) whilst the electrons themselves drift (on average) something near to 0.1 mm s^{-1}.

You may object that magnetic fields are also produced by permanent magnets (like compass needles, door catches and fridge note holders) where no current flow is evident. It turns out that even here it is electrons moving in orbit around nuclei or spinning on their own axis which are responsible for the magnetic field.

Comparison with with the Electric units

Quantity	Unit	Formula
Magnetic field strength	amperes per metre	H = Fm/le
Electric field strength	volts per metre	ε = e/d

Magnetic field strength is analogous to electric field strength. Where an electric field is set up between two plates separated by a distance, d, and having an electromotive force, e, between them the electric field is given by -

$\varepsilon = e / d$ V m^{-1}

Similarly, magnetic field strength is –

H = Fm / le

In the example the field strength is then - $H = 0.5 / 27.6\times10^{-3} = 18.1$ A m^{-1}

The analogy with electric field strength is mathematical and not physical. An electric field has a clearly defined physical meaning: simply the force exerted on a 'test charge' divided by the amount of charge. Magnetic field strength cannot be measured in the same way because there is no 'magnetic monopole' equivalent to a test charge.

Do not confuse magnetic field strength with flux density, B. This is closely related to field strength but depends also on the material within the field. The strict definition of H is

H = B / µ0 - M

This formula applies generally, even if the materials within the field have non-uniform permeability or a permanent magnetic moment. It is rarely used in coil design because it is usually possible to simplify the calculation by assuming that within the field the permeability can be regarded as uniform. With that assumption we say instead that

H = B / µ

Flux also emerges from a permanent magnet even when there are no wires about to impose a field.

A field strength of about 2000 A m^{-1} is about the limit for cores made from iron powder.

Magnetic Flux Magnetic Flux in the SI

Table 2.8

Quantity name	magnetic flux
Quantity symbol	Φ
Unit name	weber
Unit symbol	Wb
Base units	kg m2 s-2 A-1

We talk of magnetism in terms of lines of force or flow or *flux*. Although the Latin *fluxus*, means 'flow' the English word is older and unrelated. Flux, then, is a measure of the number of these lines - the total amount of magnetism.

You can calculate flux from the time integral of the voltage V on a winding -

$\Phi = (1/N)\int V.dt$ webers

This is one form of Faraday's law. If a constant voltage is applied for a time T then this boils down to -

$\Phi = V \times T / N$ Wb

How much simpler can the maths get? Because of this relationship flux is sometimes specified as *volt seconds.*

Comparison with with the Electric units

Quantity	Unit	Formula
Magnetic flux	volt second	$\Phi = V \times T$
Electric charge	amp second (= coulomb)	$Q = I \times T$

Although as shown above flux corresponds in physical terms most closely to electric charge, you may find it easiest to envisage flux flowing round a core in the way that current flows round a circuit. When a given voltage is applied across a component with a known resistance then a specific current will flow. Similarly, application of a given magnetomotive force across a ferromagnetic component with a known reluctance results in a specific amount of magnetic flux –

$\Phi = Fm / Rm$

There's a clear analogy here with Ohm's Law. You can also calculate flux as $\Phi = I \times L / N$

Flux can also be derived by knowing both the magnetic flux density and the area over which it applies:

$\Phi = Ae \times B$

A magnetic field represents energy stored within the space occupied by the field. So

$\Phi = 2W/ Fm$

where W is the field energy in joules. Or, equivalently,

$\Phi = \sqrt{(2W/ Rm)}$

Magnetic Flux Density

Table 2.9

Quantity name	Magnetic flux density,
Quantity symbol	B
Unit name	tesla
Unit symbol	T

Comparison with with the Electric units

Quantity	Unit	Formula
Magnetic flux density	webers per metre^2	$B = \Phi$ /Area
Electric flux density	coulombs per metre^2	D = C/Area

Flux density is simply the total flux divided by the cross sectional area of the part through which it flows -

$B = \Phi / Ae$ teslas

Thus 1 weber per square metre = 1 tesla. Flux density is related to field strength via the permeability

$B = \mu \times H$

So for the example core -

$B = 3.13\times10^{-3} \times 18.1 = 0.0567$ teslas

suggests that the 'B field' is simply an effect of which the 'H field' is the cause. Can we visualize any qualitative distinction between them? Certainly from the point of view of practical coil design there is rarely a need to go beyond equation TMD. However, the presence of magnetized materials modifies formula

$B = \mu_0 (M + H)$

If the B field pattern around a bar magnet is compared with the H field then the lines of B form continuous loops without beginning or end whereas the lines of H may either originate or terminate at the *poles* of the magnet. A mathematical statement of this general rule is –

div **B** = 0

You could argue that B indicates better the strength of a magnetic field than does the 'magnetic field strength' H! This is one reason why modern authors tend not to use these names and stick instead with 'B field' and 'H field'. The *definition of B* is in terms of its ability to produce a force F on a wire, length L -

$\mathbf{B = F / (I \times L \times \sin\theta)}$ Ampere's Force

Lawwhere θ is the angle between the wire and the field direction. So it seems that H describes the way magnetism is **generated** by moving electric charge (which is what a current is), while B is to do with the ability to be **detected** by moving charges.

In the end, both B and H are just abstractions which the maths can use to model magnetic effects. Looking for more solid explanations isn't easy.

A feel for typical magnitudes of B helps. One metre away in air from a long straight wire carrying one ampere B is exactly 200 nanoteslas. The earth's field has a value of roughly 60 microteslas (but varies from place to place). A largish permanant magnet will give 1 T, iron saturates at about 1.6 T and a super conducting electromagnet might achieve 15 T.

Table 2.10

Quantity name	flux linkage
Quantity symbol	λ
Unit name	weber-turn
Unit symbol	Wb-t
Base units	kg m^2 s^{-2} A^{-1}

In an ideal inductor the flux generated by one of its turns would encircle all the other other turns. Real coils come close to this ideal when the cross sectional dimensions of the winding are small compared with its diameter, or if a high permeability core guides the flux right the way round.

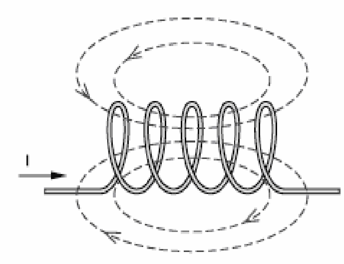


Figure 2.4 Flux Linkages

In longer air-core coils the situation is likely to be nearer to that shown in Fig.TFK: Here we see that the flux density decreases towards the ends of the coil as some flux takes a 'short cut' bypassing the outer turns. Let's assume that the current into the coil is 5 amperes and that each flux line represents 7 mWb.

The central three turns all 'link' four lines of flux: 28 mWb.
The two outer turns link just two lines of flux: 14 mWb.

We can calculate the total 'flux linkage' for the coil as:

$\lambda = 3\times28 + 2\times14 = 112$ mWb-t

The usefulness of this result is that it enables us to calculate the total self inductance of the coil, L:

$L = \lambda/I = 112/5 = 22.4$ mH

In general, where an ideal coil is assumed, you see expressions involving $N\times\Phi$ or $N\times d\Phi/dt$. For greater accuracy you substitute λ or dλ/dt.

Table 2.11

Quantity name	Inductance
Quantity symbol	L
Unit name	henry
Unit symbol	H
Base units	kg m2 s-2 A-2

Comparison with with the Electric units

Quantity	**Unit**	**Formula**
Inductance	webers per amp	$L = \Phi/I$
Capacitance	coulombs per volt	$C = Q/V$

Any length of wire has inductance. Inductance is a measure of a coil's ability to store energy in the form of a magnetic field. It is defined as the rate of change of flux with current -

$L = N \times d\,\Phi / d\,I$

If the core material's permeability is considered constant then the relation between flux and current is linear and so:

$L = N \times \Phi / I$

By Substitution of Equation TMM and Rowland's Law -

$L = N^2 / Rm$

You can relate inductance directly to the energy represented by the surrounding magnetic field -

$L = 2\,W / I^2$

Where W is the field energy in joules.

In practice, where a high permeability core is used, inductance is usually determined from the Al value specified by the manufacturer for the core -

$L = 10^{-9}\,Al \times N^2$

Inductance for the toroid example is then:

$L = 2200 \times 10^{-9} \times 2^2 = 8.8\ \mu H$

If there is no ferromagnetic core so μr is 1.0 (the coil is 'air cored') then a variety of formulae are available to estimate the inductance. The correct one to use depends upon

- Whether the coil has more than one layer of turns.
- The ratio of coil length to coil diameter.
- The shape of the cross section of a multi-layer winding.
- Whether the coil is wound on a circular, polygonal or rectangular former.
- Whether the coil is open ended, or bent round into a toroid.
- Whether the cross section of the wire is round or rectangular, tubular or solid.
- The permeability of the wire.

- The frequency of operation.
- The phase of the moon, direction of the wind etc..

Table 2.12

Quantity name	inductance factor
Quantity symbol	A_l
Unit name	Nanohenry
Unit symbol	nH
Base units	kg m^2 s^{-2} A^{-2}

A_l is usually called the *inductance factor*, defined

$A_l = L \times 10^9 / N^2$

If you know the inductance factor then you can multiply by the square of the number of turns to find the inductance in nano henries. In our example core A_l = 2200, so the inductance is -

$L = 2200 \times 10^{-9} \times 2^2 = 8800$ nH = 8.8 µH
The core manufacturer may directly specify an A_l value, but frequently you must derive it via the reluctance, R_m. The advantage of this is that only one set of data need be provided to cover a range of cores having identical dimensions but fabricated using materials having different permeabilities.
$A_l = 10^9 /$ Rm So, for our example toroid core –

$A_l = 10^9 / 4.55 \times 10^5 = 2200$

The inductance factor may sometimes be expressed as "millihenries per 1000 turns". This is synonymous with nanohenries per turn and takes the same numerical value.

If you have no data on the core at all then wind ten turns of wire onto it and measure the inductance (in henrys) using an inductance meter. The A_l value will be 10^7 times this reading.

A_l values are, like permeability, a non-linear function of flux. The quoted values are usually measured at low (<0.1 mT) flux.

Table 2.13 Reluctance

Quantity name	reluctance
Quantity symbol	Rm or $\mathfrak{R}$
Unit name	per henry or ampere-turns per weber
Unit symbols	H-1
Base units	A2 s2 kg-1 m-2

Reluctance is the ratio of mmf to flux -

$R_m = Fm / \Phi$

In a magnetic circuit this corresponds to Ohm's Law and resistance in an electric circuit. Compare
$R_e = V / I$

Reluctance is also proportional to the core factor, Σl/A, but inversely proportional to permeability -

$R_m = (\Sigma l/A) / \mu$

Again, compare
$R_e = (\Sigma l/A) / \sigma$

where σ is the electrical conductivity of a conductor of given length and cross-sectional area.
Take care to use the absolute rather than the relative permeability here. So for the toroid example reluctance is then:
$R_m = 1420 / 3.13\times10^{-3} = 4.55\times10^{5}$ A-t Wb^{-1}
A magnetic field represents stored energy and
$R_m = 2\ W / \Phi^2$
Equation TMR

where W is the energy in joules.

Although it can be a useful concept when analyzing series or parallel combinations of magnetic components reluctance is, like permeability, non-linear and must be used carefully.

You could be forgiven for thinking that there would be no need to spell out what current is. That's obvious surely? Your mistake is to forget how hard all writers on electromagnetism strive to obfuscate an already difficult subject. Here's the problem.

When considering the magneto-motive force it makes no difference whether you have twelve turns of wire carrying one amp, or three turns carrying four amps, or two turns with six amps. As far as the mmf goes it's all just 'twelve ampere-turns'. You will get just the same magnetic field in each case.

Reasoning that detail about the number of turns and the number of amps doesn't matter, only the **product of the two**, some writers decide to say that the current **is** twelve amps. They write I = 12 A and leave it to you to decide which scenario brought about that 'current'. This insidious practice carries over to formulae as well.

Which is fine as long as it's consistent and clear to the reader what's happening. If the current changes then, by Faraday's Law we have an induced voltage. You then have to remember that the induced voltage is **per turn** and not the the total coil voltage. Ambiguity starts to creep in.

It depends, perhaps, on whether you're more interested in physics or engineering. These pages take the latter view and distinguish current from mmf. Current here, then, is what an ammeter reads, and the number of coil turns, N, is written explicitly.

The physicists get their way in the end because, although you might just speak of reluctance as 'ampere-turns per weber', inductance as 'weber-turns per ampere' is getting a little contrived - even if it does reflect the concept of flux linkage rather nicely. But permeability as 'weber-turns per ampere-metre'?

Trivia point: why is the symbol I used for current? Allegedly, it stands for 'electric *intensity*', as opposed to 'total amount of electricity' (charge). Maxwell, though, used the symbol C for current and used electric intensity to refer to the E-field: what most people today know as electric field strength. So it goes.

Current density in the SI
Table 2.14

Quantity name	current density
Quantity symbol	J
Unit name	amperes per square metre
Unit symbol	A m-2

Current density is simply the total electric current divided by the area over which it is flowing. Example: if a wire 0.7 millimetres diameter carries a current of 0.5 amperes then the current density is

$J = 0.5 / (\pi\ 0.0007^2 / 4) = 1.30\times10^6\ A\ m^{-2}$

Or 1.3 amps per millimetre^2. A reasonable limit for most small transformers is $3.5\times10^6\ A\ m^{-2}$.

The number of turns

By tradition, coil calculations use the capital letter N to represent the total number of turns in the coil. Solenoid coils are sometimes described using the lower case letter n to represent the number of turns per unit length. So

$N = n \times l_a$

Where l_a is the axial length of the coil.

Naturally, for most designs, the number of turns required is the $64,000 question. The answer comes in a bewildering variety of forms. For the most common case, such as the example toroid core, where the manufacturer has specified Al -

$N = \sqrt{(10^9\ L / Al)}$
So, if you needed 330 microhenries then
$N = \sqrt{(10^9 \times 330 \times 10^{-6} / 2200)} = 12$ turns
Relationships between magnetic quantitiesFlux, field strength, permeability, reluctance ..... it's easy to go into jargon overload.
Snelling lists over 360 different symbol uses connected with ferromagnetics. There isn't even agreement about what to call some properties (I say remnance, you say remanence, he says retentivity). You will cope better if you can form a mental picture of the party that these names throw when they get together inside your transformer.

Analogy with electric quantities

You may find it easier to obtain an intuitive grasp of the relationships between magnetic quantities by thinking in terms of 'magnetic circuits' with flux flowing round a core in a fashion analogous to current flowing round an electric circuit.

Electric analogues

Table 2.15

Magnetic	Electric
quantity	quantity
magnetomotive force	electromotive force (voltage)
magnetic field strength	electric field strength
permeability	conductivity
magnetic flux	current
magnetic flux density	current density
reluctance	resistance

For example, if you have a transformer with a gapped core then imagine that the core and the gap form a series magnetic circuit with the same flux flowing through both reluctance components in an analogous fashion to a series electric circuit in which the same current flows through two resistors -

$Fm = \Phi \times (Rm\_gap + Rm\_core)$ ampere-turns

compare

$V = I \times (R1 + R2)$ volts

There's an entire family of formulae which take similar forms in both the electric and magnetic worlds. Kraus lists most of them.

All analogies break down when pushed too far. This one falls rather quickly if you realise that curent flowing through a resistor dissipates energy while flux flowing through a reluctance does not. In fact you can ask whether flux is a real physical effect at all (in the way that electron flow is).

Sequence of operation

In transformer design you would normally like to deal in terms of the voltages on the windings. However, the key to understanding what happens in a transformer (or other wound component) is to realize that what the transformer really cares about is the **current** in the windings; and that everything follows on from that.

- The **current** in a winding produces **magneto-motive force -**

  $Fm = I \times N$ ampere-turns

- The magneto-motive force produces **magnetic field -**

  $H = Fm / le$ ampere-turns per metre

- The field produces **magnetic flux density -**

  $B = \mu \times H$ tesla

- Summed over the cross-sectional area of the core this equates to a **total flux -**

  $\Phi = B \times A_e$ webers

- The flux produces **induced voltage** (EMF) **-**

  $e = N \times d\Phi/dt$ volts

If you can follow this five step sequence then building a mental image of a magnetic component becomes simpler. Remember, you put in a current and get back an induced voltage. In fact, if you can treat the permeability as being linear, then the constants N, le, µ and Ae can be lumped together into one constant for the winding which is called (surprise!) Inductance, L -

$L = \mu \times A_e \times N^2 / le$ henrys

I give the base units for all the quantities in this equation; enabling thrill-seekers to make a dimensional analysis verifying that it is consistent. Right, so then our five step relationship between current and EMF boils down to:

$e = L \times dI /dt$ volts

You may be about to complain that you know the EMF on your winding but don't know the current in it. The answer is that the process then works in reverse - the current will build up until the induced voltage is sufficient to oppose the applied voltage. You can find out more by looking at Faraday's law.

How do you take into account the presence of the secondary windings in a transformer? One way is to take the first four steps of the sequence above and apply them separately to each winding (whether primary or secondary). The arithmetic sum over all windings gives total core flux. From the time rate of change of flux you then have the induced voltage in each winding (since you also know the number of turns for each). There are less tedious methods of analyzing transformer operation which you would probably do better using. But they are another story.

2.2 Magnetic phenomena in ferromagnetic materials

Ferromagnetism is one of magnetic state of the substances characterized by parallel orientation of the magnetic moments of nuclear carriers of magnetism. It is caused by positive value of energy of inter-electronic exchange interaction. The magnetic permeability of ferromagnetic materials is positive and reaches values of about 10^5 G/Oe. Their magnetization J grows with increase of magnetic field H not linearly and achieves a limit value Js (magnetic saturation). Value J depends also on "magnetic history" of a sample. It makes dependence J on H ambiguous, so the magnetic hysteresis curve is observed.

Ferromagnetic hysteresis curve (loop) characterized by several parameters: coercivity, remanence (or remanent magnetization), magnetization of saturation, maximum energy product (or strength of the magnet). Coercitivity Hc is the field which has to be applied to ferromagnetic material to make magnetization equal to zero. High coercitivity is very important for permanent magnets to stay magnetized in the presence of an opposing magnetic field. On the contrary for magnetic transformers the big coercitivity is harmful because it increases the lost of energy. Remanence is residual magnetization of a ferromagnetic material in the absence of external magnetic fields (after the external magnetizing field has been turned off). This parameter is convenient to use for comparison of the relative “strength” of different magnets. It depends greatly on magnet composition and method of manufacture. Magnetization of saturation is magnetization of ferromagnetic material in very strong (infinity strong) magnetic fields. All the atoms in this case are magnetized in one direction. Strength of the magnet is the area of hysteresis loop. This gives a measure of the energy stored in the magnet. The usual unit is the Mega Gauss-Oersted (MGOe). The SI unit is kJ/m^3. [1 MGOe = 8 kJ/m^3].

Iron, nickel, cobalt, some of the rare earths (gadolinium, dysprosium) exhibit ferromagnetic properties. Most of these materials have poly-crystalline form. Samarium and neodymium in alloys with cobalt have been used to fabricate very strong rare-earth magnets. Such magnets have very high coercivity, remanence, maximum energy product. On the contrary some of amorphous (non-crystalline) ferromagnetic metallic alloys exhibit low coercivity, low hysteresis loss and high permeability. Such amorphous alloys can be fabricated by very rapid quenching (cooling) of a liquid alloy (usually Fe, Co, or Ni with B, C, Si, P, or Al). One example of such an amorphous alloy is $Fe_{80}B_{20}$ (Metglas 2605).

Ferromagnetism is a so-called cooperative phenomenon, as single atoms cannot exhibit ferromagnetism, but once a certain number of atoms are bound together in solid form, ferromagnetic properties arise. If a ferromagnetic material is cooled from above the Curie temperature, microscopic domains with nonzero magnetization form. Domains are spontaneously magnetized up to saturation. They usually have linear sizes of about 10^{-3}-10^{-2} cm. The Curie temperature gives an idea of the amount of energy takes to break up the long-range ordering in the material. The Curie temperature of iron is about 1043 K, which corresponds to the thermal energy of about 0.135 eV.

In absence of an external magnetic field the magnetization vectors of the different domains are oriented in opposite directions, so the net magnetization of the material is zero. Such domain configuration diminishes the energy of magnetic field generated by ferromagnetic material in external space. The direction of vectors of domains magnetization coincides usually with a direction of easy magnetization axes, that provides the minimum of free energy of ferromagnetic material. If the size of ferromagnetic material is less then a critical size, then splitting into domains can become energetically unprofitable and one-domain structure is formed. Such case is shown in animation (each arrow represents one magnetic domain). In practice such case can be realized in ferromagnetic films and amorphous alloys. If the axis of easy magnetization coincides with a direction of applied field H, then magnetization occurs by means of domain walls motion. Thus, if an external magnetic field is increased in the direction opposite to material magnetization, then the flip of magnetization occurs sharply when H=Ha , where Ha is a value of anisotropy field. The rectangular hysteresis loop is observed and coercivity Hc equals to Ha.

In a case when the axis of easy magnetization is perpendicular to applied field H, the magnetization occurs by domains rotation and linear hysteresis loop observed. Such ferromagnetic materials can be used in measuring systems and transformers since their magnetization is directly proportional to applied magnetic field (or, for example, to a current in primary windings of a transformer). In such ferromagnetic materials the effect of Young's modulus change under action of magnetic field (□E-effect) is observed. In amorphous alloys, for example, this effect can be great enough (Young modulus can be varied an order of magnitude by magnetic field).

Two nearest domains magnetized in opposite directions are always separated by a transitive layer of final thickness (Bloch Wall) in which there is a gradual turn of spins as it is shown in animation. Generally the magnetization of ferromagnetic materials occurs both by means of domains rotation and motion of domain walls. Presence of impurities in a magnetic material, defects of a crystal lattice, various sorts of non-uniformity complicates the movement of Block walls and by that raises the coercitivity H_c of a material.

Magnetostriction is a change of the form and the sizes of a ferromagnetic material during magnetization. This phenomenon was discovered in 1842. In such ferromagnetic materials as Fe, Ni, Co, in a number of alloys and ferrites the magnetostriction can achieve significant value (of about 10^{-6}-10^{-2}). Animation shows a strip domain structure with an axis of easy magnetization perpendicular to applied field H. Magnetization is accompanied by rotation of domains that results in change of the size of a magnetic material (magnetostriction). Magnetostriction has a wide range of applications in techniques. This phenomenon underlies magnetostriction converters and relay lines, generators and receivers of ultrasound, filters and stabilizers of frequency, etc.

2.3 Magnetics Properties of Transformers

The magnetic properties are characterized by its hysterisis loop, which is a graph of flux density versus magnetization force as shown below:

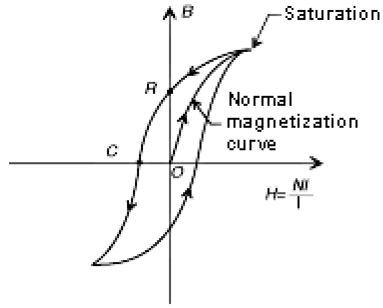


Fig 2.5

When a electric current flows through a conductor (copper wire), it generate a magnetic field. The magnetic field is strongest at the conductor surface and weakens as its distance from the conductor surface is increased. The magnetic field is perpendicular to the direction of current flow and its direction is given by the right hand rule shown below

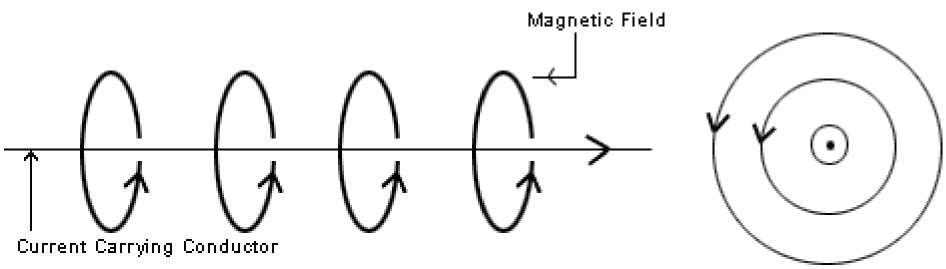


Fig 2.6

When the conductor or wire is wound around a magnetic materials (ferrite, iron, steel, MPP, sendust, high flux, etc), and current flows through the conductor, a flux is induced on the magnetic materials. This flux is induced by the magnetic field generated by the current carrying conductor. The magnetic material's atomic parts got influenced by the magnetic field and causes them to align in a certain direction.

The application of this magnetic field on the magnetic materials is called magnetization force. Magnetization force is called Oersted or A/m (amperes per meter).

The units for Magnetization force is "H"

The results of applying these magnetic field from the current carrying conductor causes the magnetic materials to have magnetic flux being formed inside the magnetic materials. The intensity of these flux is called flux density. Therefore flux density is defined as the flux per square area.

Flux density is called gauss or Tesla. I Tesla is10,000 gauss, or 1mT is 10 gauss.

The unit for Flux is "B"

Thus, the hysterisis loop is often called the BH curve. Understanding of the BH curve is extremely important in the designs of transformers, chokes, coils and inductors.

Flux density or B is given as

$$B = \frac{E \times 10^8}{4\,A\,N\,f}$$

E= Input or Output Voltage, in volt (rms)
A= Cross Sectional Area, in cm^2
f = Switching frequency, in Hz
N= Number of Turns

Note that B is a function of voltage (input voltage if calculated from primary windings, and output voltage if calculated from secondary side). Flux will reduce if you increase the number of turns

The magnetization force or H is given as

$$H = \frac{0.4\pi NI}{\ell}$$

Where N = No. of turns

I = Current in Amps

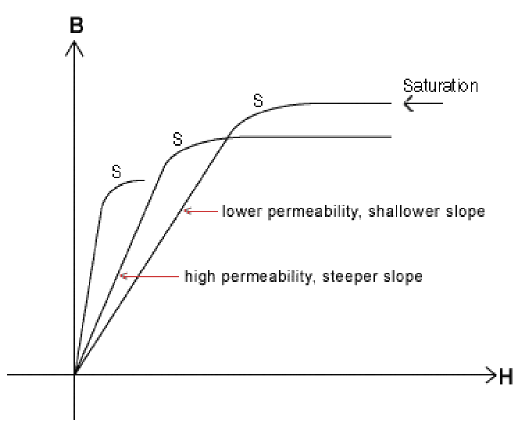
ℓ= Magnetic Path Length in cm

Note that H is a function of input current. As the current swings from positive to negative the flux changes as well, tracing the curve.

The permeability of a magnetic material is the ability of the material to increase the flux intensity or flux density within the material when an electric current flows through a conductor wrapped around the magnetic materials providing the magnetization force.

The higher the permeability, the higher the flux density from a given magnetization force.

If you look at the BH loop again, you will note that the permeability is actually the slope of the BH curve. The steeper the curve, the higher the permeability as shown below.



As the magnetization force increases (or the current over the conductor is increased), a point is reached where the magnetic material or core will saturate. See point "S" above on the curves. When that happens, any further increase in H, will not increase the flux. More importantly, the permeability goes to zero as the slope now is flat.

In this situation the magnetic material or core will fail to work as a transformer, chokes, or inductors.

In a transformer design, you must make sure that the maximum AC current swings from positive to negative is well below the saturation point.

Fig 2.7

Another way to get saturation is by increasing the flux density which is normally achieved by increasing the voltage (see equation above).

$$B = \frac{\text{Voltage} \times 10^8}{4\,A\,N f}$$

From the BH curve, you can see that when the permeability is high (slope is steep), the cores will go into saturation faster. Conversely, when the permeability is low, the cores saturate at a much higher flux density.

2.4 Typical construction of a transformer core

A photo of a typical core of a transformer (rating 400 kVA) is shown in Figure 2. The yokes and the legs of the core have stepped cross-sectional areas formed by a stacked arrangement of thin laminations. Each layer of lamination has an average thickness of 0.28mm. Considering its physical details, a lamination on its own is a flimsy layer. These laminations, although clamped at certain points, still can have a freedom for relative in-plane motions over their remaining interface areas. As laminations may not have good matching flat surfaces and as they are not clamped together over an entire surface area, residual gaps between the laminations are unavoidable. Magneto-motive forces acting across these air gaps could set relative transverse motions between the laminations. Also, with clamped constraint points in place, deformation due to magnetostriction could set additional bending of the lamination plates.
Therefore, it seems interesting to study in detail the effect of laminations on the flexibility of the core structure. A preliminary study of these effects is presented in the following sections.

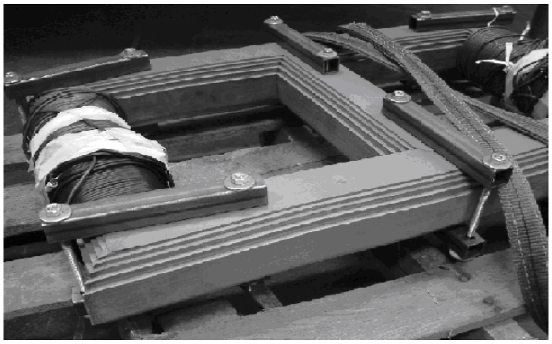


Fig 2.8 Transformer core and Laminations

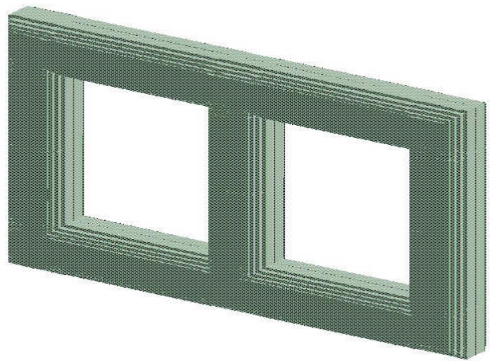


Fig 2.9 Core arrangement in a transformer

PROPERTIES OF GRAINS, DOMAINS AND UNDERSTANDING OF HYSTERISIS LOSSES

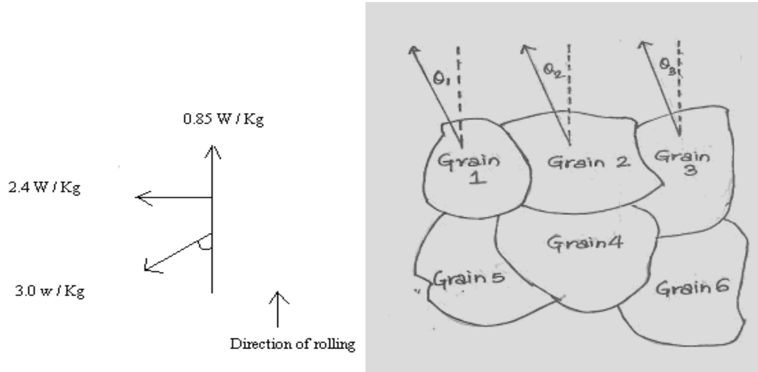
Every type of steel has "grains" which consist of "domains". These "domains" are nothing but electrical charges oriented in any random direction. Therefore if a transformer were to be made of Mild Steel used as core material, the core loss would be approx. 16 to 17 w/kg at 1.5T/50Hz and the size of the transformer would be approx. 18 to 20 times the size of a transformer manufactured with GO steels.

The main difference between regular "carbon" steels and GO steels are:

1. The size of the "grains" in GO steels are purposely "grown" and made bigger and are about 10 times the size of the grains in regular steel, thereby reducing the hystereses losses. The size of grains in CGOS is 2 mm to 5mm and HGOS is 5mm to 20mm. In regular steels the size of a grain is less than 0.5mm.
2. The grains in GO steels are all aligned almost parallel to the direction of rolling of the steel (i.e. the length of the steel). The angle of mis-orientation (i.e. deviation from the rolling direction) is maximum 7% for conventional GO and less than 3% for Hi-B GO steels. This reduces the hystereses losses as "switching" (explained later) becomes easier within the domains.
3. The chemical composition of the GO steels has about 3.2% of Silicon as an alloy, thereby increasing the specified volume resistivity of the steel, thereby reducing the eddy currents. GO Steels are also decarbonised and have no more than 0.06% of carbon in their chemical composition, which prevents aeging of the steel.
4. There is a special carlite insulation coating on the steel, which reduces the inter-laminar eddy current losses within the core.

Let us understand how exactly hystereses losses are developed with respect to GO electrical steels: The microstructure of the steel, as mentioned before, consists of numerous "grains" each of which have domains. The magnified diagram would look like this:

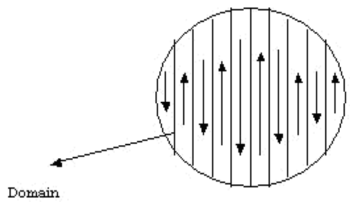
Typical core loss for M4 grade at 1.5 Tesla/50 Hz in this direction

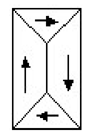


…..Fig 2.10

O = Angle of misorientation from Rolling direction Grains which is less than 7% for CGOS and less Than 3% for HGOS

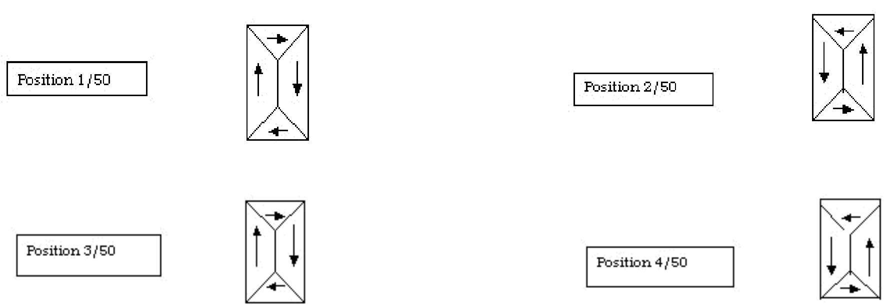
The typical picture inside any "grain" would consist of domains like this:



A domain when expanded would look like this: 

Thus, every domain is nothing but a closed magnetic circuit as shown in the figure above.

Now consider what happens when an alternating current of 50 cycles is applied. The domains "switch" to and fro 50 times in a second. Therefore the domain looks like this as the current alternates 50 times and the diagrams below represent the direction of the domain as the current alternates



And so on ….. 50 times every second

It is relatively very easy for the vertical switches (V1 and V2) to occur but very hard for the horizontal (H1 and H2) switches to occur.

The horizontal switches require more energy to be completed and also "lag" behind the vertical switches, and this results in heat, which results in the hystereses loss within the steel. The sum total of the energy required for the horizontal switches to occur are the total hystereses losses of the steel. Thus the larger the grains, the lower the losses as there are less total number of grains in the steel and therefore less number of "switches" and low hysterisis losses.

PROCESSING OF CRGO STEEL INTO LAMINATIONS

CRGO steel is a "delicate" steel to be handled with care. As the magnetic property of the steel and not the tensile strength (as is the case with most other steels) is the important quality required, it is imperative that we understand the nuances in handling, storing and processing of this steel. If these are not done properly, it ultimately leads to higher losses and the results are not as per design.

Stresses are of two types, elastic stress and plastic stress. An elastic stress is a temporary stress which any GO steel may be subjected to like some load on top of the coil or a slight force to decoil. The moment the stress is removed, the original magnetic properties of the material are restored and these are no longer damaged.

However, a plastic deformation due to winding into cores or pulling or stretching or bending GOS as shown below, can only be rectified by a stress relief annealing at around 820ºC.

1. Storage of CRGO coils has to be done properly as improper storage may result in excessive stresses unintentionally. This type of stress can be elastic or plastic depending on the severity of the wrong storage and the resulting deformation in coil shape (if any).

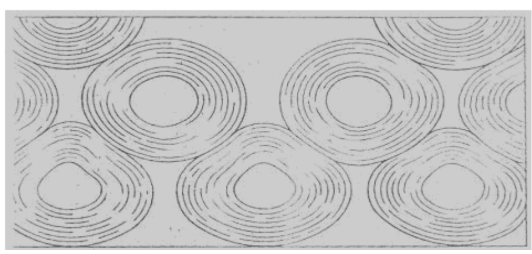


Fig 2.11 Introduction of stress in steel due to improper storage of coils

CRGO is an important raw material which forms the core of the transformer.

1. Proper care is to be used in handling of strip, sheets or long laminations, failing which can introduce stresses that can distort magnetic properties

2 .The method of holding the laminations in a core assembly and the mechanical pressure applied to the core assembly also affects the total core loss. Uninsulated bolts or assembly by welding, would provide a low resistance path and increase eddy current losses and should therefore be avoided. High assembly

pressures decrease the surface resistance and increase the inter-laminar losses and increase the total core losses. Therefore excessive clamping on the core must be avoided as the resistance of surface insulation is inversely proportional to the pressure applied. A high clamping pressure leads to breakdown of surface insulation resistivity and higher inter-laminar losses.

3. Inaccurately cut angles in mitred cores also result in a distortion of flux and increase in overall core losses. Air gaps at joints can drastically alter the values of t he total core loss.

4. Variation in thickness in the same width step of material not only results in problems in core building, but also increases the overall core loss of the material as it increases the air gaps during the assembly.5. Residual material on lamination surfaces like oil, dust etc. also adversely affects the stacking factor and increases the total core loss.

Table 2.16

Sound Levels: Maximum sound levels are as follows:

AUDIBLE SOUND LEVELS for	
LIQUID FILLED TRANSFORMERS	
KVA	**Sound Level**
	(dBA)
0-9	40
10-50	45
51-150	50
151-300	55
301-500	60

KVA	**Sound Level**
700	57
1000	58
1500	60
2000	61
2500	62
3000	63
4000	64
5000	65
6000	66
7500	67
10000	68
12500	69

15000	70
Data are based on OA rating for oil-immersed power	

Chapter-3

3 TRANSFORMERS EQUATIONS

3.1 Magnetic circuit excited by alternating current

According to the Faraday's experiment the voltage *e* induced in one turn linking a changing magnetic field (see Fig.3.1) is proportional to the time rate of change of flux *Φ*:

$$e = \frac{d\Phi}{dt} \qquad \text{............1}$$

The polarity of the induced voltage can be determined by the Lenz's law that says:
"The induced voltage is always in such a direction as to tend to oppose the change in flux linkage that produces it"

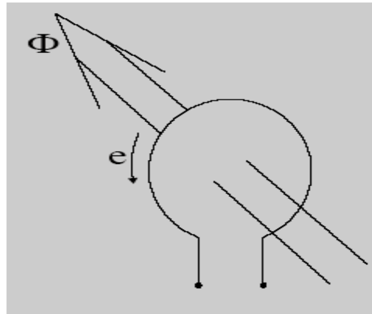


Fig.3.1 Explanation to equation (1)

This is shown in 3.1. For multitern coil the induced voltage is:

$$e = N\frac{d\Phi}{dt} = \frac{d\lambda}{dt}$$

…………2

where:
N – is the number of coil turns and
λ – is the flux linkage in weber turns.
Suppose we have a coil wound on one leg of a close iron core as shown in Fig.3.2. To draw an equivalent circuit of such a device called inductor, and then to analyze its behavior under variable supply condition let we consider first an ideal inductor.

An ideal inductor

An ideal inductor is defined by the following assumptions:
• The coil of inductance L has the resistance R equal to zero,
• There is an ideal magnetic circuit of the iron core with no power losses in it,
• There is no leakage flux, what means that the whole magnetic flux is within the iron core.

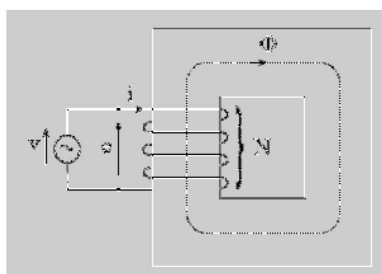


Fig.3.2 Scheme of the inductor supplied from the ac. source

Assuming a linear relation between current and flux, the sinusoidal current
i* =*Im *sin(*ωt *)* ………. (3)
produces the sinusoidal flux

$$\Phi = \Phi_m \sin(\omega t)$$

………….(4)

The voltage induced in N-turn coil is

$$e = N\frac{d\Phi}{dt} = N \cdot \omega \cdot \Phi_m \cdot \cos(\omega t) = E_m \cos(\omega t)$$

……(5)

The effective value of this voltage is:

$$E = \frac{E_m}{\sqrt{2}} = \frac{N\omega\Phi_m}{\sqrt{2}} = \frac{2\pi}{\sqrt{2}} Nf\Phi_m = 4.44Nf\Phi_m \qquad \text{……...(6)}$$

The voltage expressed in terms of current flowing trough the coil is:

$$e = L\frac{di}{dt} \qquad \text{…….(7)}$$

For sinusoidal current:

$$e = L\omega I_m \cos\omega t = E_m \cos\omega t \qquad \text{…….(8)}$$

The effective value of the voltage expressed in the complex form is:

$$\underline{E} = jX_\mu \underline{I} \qquad \text{……(9)}$$

where ***X L*** µ ω = is the magnetizing reactance.
For an ideal inductor, the induced voltage (*emf – E*) is equal to the voltage supply
E= V .
The equivalent circuit of such an inductor is shown in Fig.3.3. The phasor diagram of voltages and current is shown in Fig.3.4.

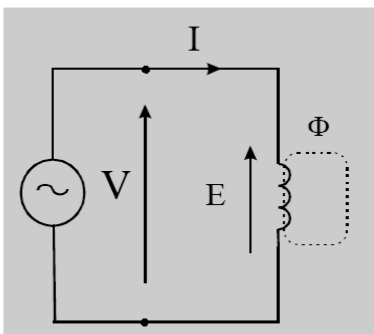


Fig.3.3 Inductor equivalent circuit

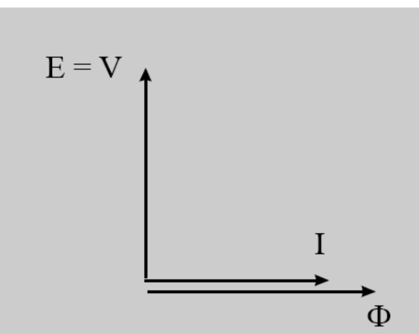


Fig.3.4 Phasor diagram corresponding with Fig.3.3

1.2 A real inductor

A real inductor has a real coil and the real magnetic circuit. This magnetic circuit is described by the hysteresis loop of B-H characteristic shown in Fig.3.5. During the process of magnetization by the alternating flux the energy is lost due to the hysteresis loop. This energy loss, called the hysteresis loss is proportional to the area closed by the hysteresis loop. That means it depends on the material the inductor core is made of. The empirical formula for this loss is:

$$\Delta P_h = K_h f \cdot B_m^n \qquad \text{……….. (10)}$$

where the constant ***Kh*** and *n* vary with the core material. *n* is often assumed to be 1.6 – 2.
Since, according to equation (6) *B* is proportional to *E* we can write for *n=2*

$$\Delta P_h = K_h' \frac{E^2}{f}$$

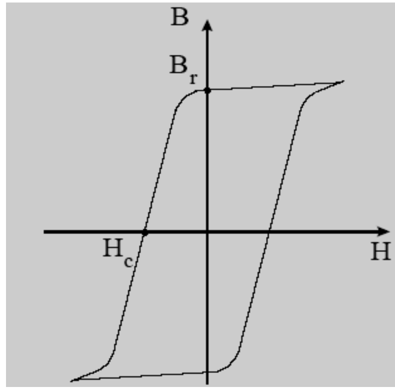


Fig.3.5 Hysterisis loop of B-H characteristic

There is another source of power loss in the magnetic core too. These are eddy currents induced in the core. To illustrate this phenomenon let us consider the solid core shown in Fig.3.6.a. If the magnetic flux existing in the core is directed towards the paper and is increasing, it induces the voltages in the core, which, in the case of close electric loops, cause the eddy currents that generate the power losses ***i R*** 2 as a heat. The power losses can be reduced by decreasing *i* (increasing *R*). If, instead of a solid iron core, thin laminations are used (Fig.3.6.b), the effective induced currents are decreased by the increase of the resistance of the effective paths. The eddy current losses are significantly reduced in that case.

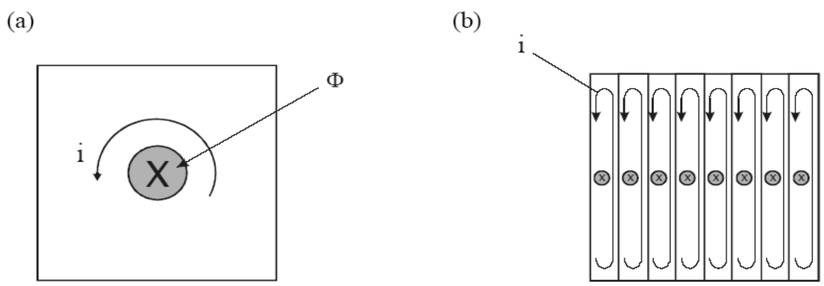


Fig.3.6. Eddy currents in: (a) solid iron core, (b) laminated iron core

For the given core, the eddy currents power losses are given by

$$\Delta P_e = K_e f^2 B_m^2 \quad \text{…………(12)}$$

Since the voltage induced in the coil is proportional to ***f Bm*** · , the power losses are equal to:

$$\Delta P_e = K_e' E^2 \quad \text{………….(13)}$$

The constant ***Ke '*** depends on the conductivity of the core material and the square of the thickness of the laminations.

Combining the eddy currents and hysteresis power losses the total core power losses are:

$$\Delta P_{Fe} = \Delta P_h + \Delta P_e = K_{Fe} f^{1.3} B^2$$

………… (14)

For the purpose of the equivalent circuit we intend to build, an equivalent resistance ***RFe*** is introduced. Then the core power losses at constant supply frequency can be expressed as follows:

$$\Delta P_{Fe} = \frac{E^2}{R_{Fe}}$$

……….. (15)

The power losses Δ***PFe*** are proportional to the square of voltage *E*, which appears across the resistance ***RFe***. This allows to show the inductor equivalent circuit in form as in Fig.3.7a.

(a) (b)

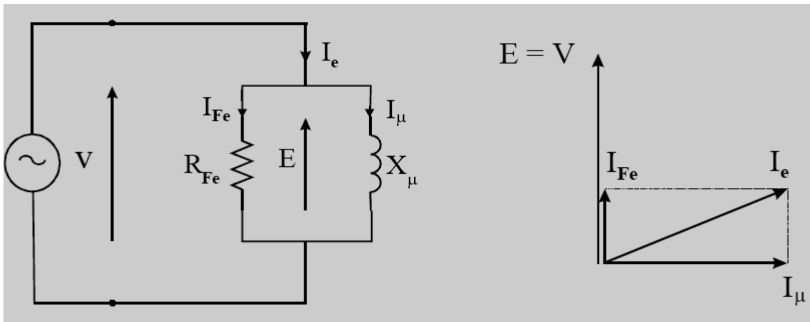


Fig.3.7 An equivalent circuit (a) and the corresponding phasor diagram (b) of the inductor with core losses

The excitation current ***Ie*** is split into two components: the magnetizing current ***I*** μ and ***IFe***, proportional to the core power losses. Fig.3.7.b, with the phasor diagram shows the relationship between the voltage *E* and currents ***I*** μ and ***IFe***. These currents are displaced from each other by an angle $\pi/2$. This displacement can be explained by means of excitation current waveform shown in Fig.3.8. If the coil is supplied with sinusoidal voltage the flux Φ must be sinusoidal too according to equation 1. Since the magnetizing characteristic B-H is nonlinear, and has a hysteresis loop, the current waveform obtained from magnetizing curve is far from sinusoidal. If we extract two current components from the current *ie* by finding the symmetrical currents with regard to the *l* line we obtain ***ih*** current being in phase with the voltage *E* and magnetizing current ***I*** μ lagging the voltage *E* by the angle $\pi/2$ (see Fig 3.7).

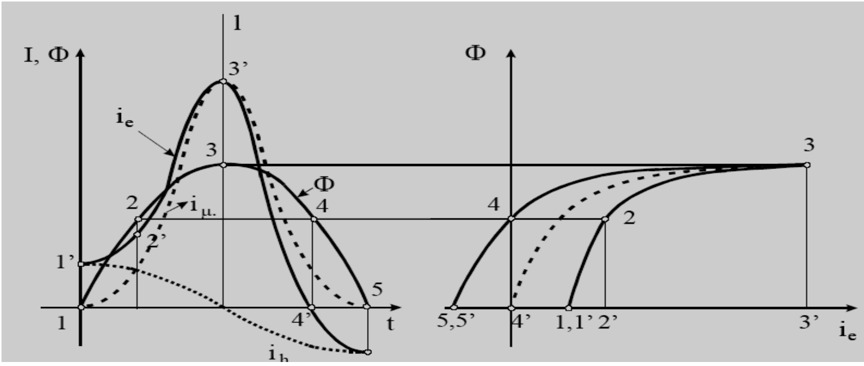


Fig.3.8 Extraction of hysteresis current component ***ih*** from the excitation current *ie*

So far we did not take into account the resistance of the coil *R* and the leakage flux Φ***s***. This is the flux, which goes via air as shown in Fig.3.9. It induces the voltage ***Es*** in the coil, which is equal

$$e_s = N\frac{d\Phi_s}{dt} \qquad \text{………… (16)}$$

If we express the flux Φ***s*** in terms of the current:

$$\boldsymbol{\Phi_s = L_s i}, \qquad \text{…………. (17)}$$

then the voltage:

$$e_s = L_s\frac{di}{dt} = L_s\omega I_m \cos\omega t \qquad \text{…………. (18)}$$

or written in complex notation:

$$\underline{E}_s = jX_s\underline{I} \qquad \text{………….(19)}$$

where ***Xs*** is the leakage reactance.

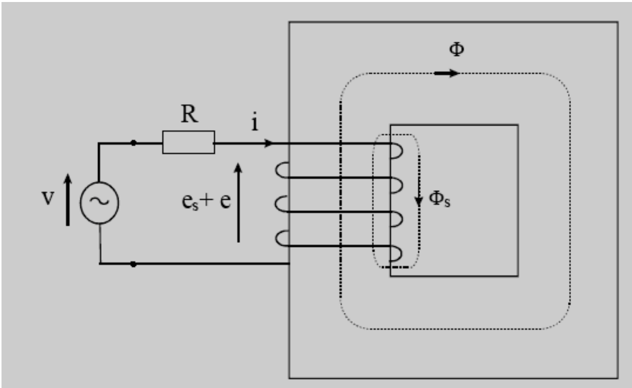


Fig.3.9 Diagram of the real inductor with the coil resistance *R* and the leakage flux Φ***s***

The equivalent circuit of the real inductor is shown in Fig.3.10.a. The circuit shows magnetic fluxes associated with their inductances ***Ls*** and ***L***μ. The voltage equation of the circuit is

$$\underline{V} = \underline{E} + (R + jX_s)\underline{I} \qquad \text{………………(20)}$$

An adequate phasor diagram is shown in Fig.3.10.b.

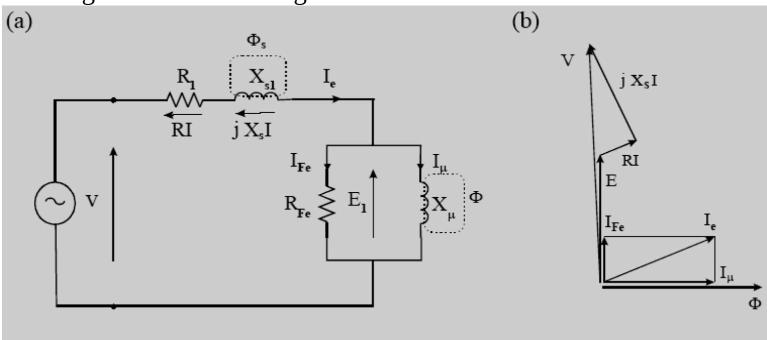


Fig.3.10 Equivalent circuit (a) and phasor diagram (b) of the real inductor

3.2 Single-phase transformer

3.2.1. Transformer operation and construction

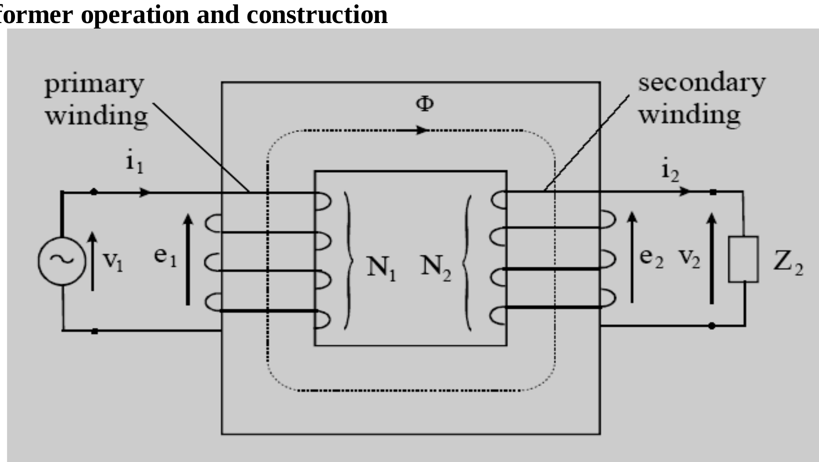


Fig.3.11 Two-winding single-phase transformer

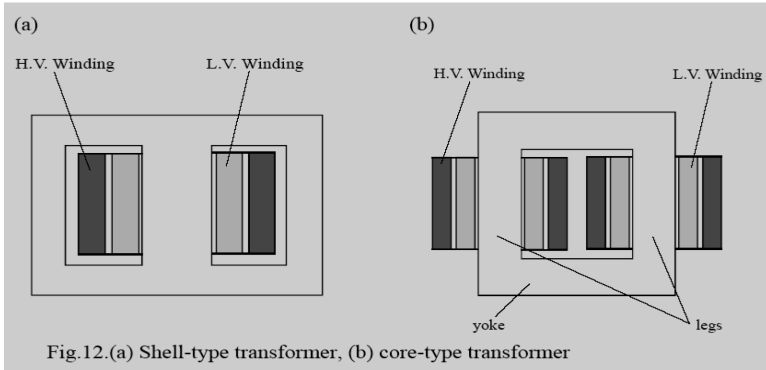


Fig.3.12.(a) Shell-type transformer, (b) core-type transformer

Two cooling systems:
- air-cooled: small transformers
- oil-cooled: large transformers

Very large transformers are immersed in the tanks with radiators and forced circulation.

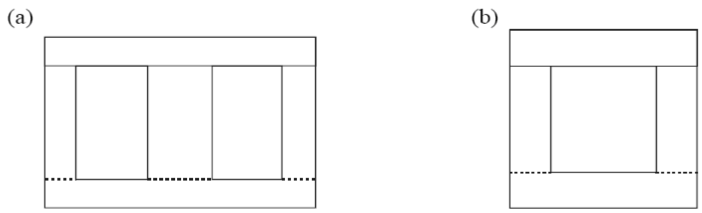


Fig.3.13. Construction of transformer cores from stampings: (a) shell-type and (b) coretype transformer

3.2.2. Ideal transformer

Assumptions for an ideal transformer:
- ***R***1 and ***R***2 are equal to 0
- Φ***s***1 and Φ***s***2 are equal to 0 (μ= ∞ and ***L*** = ∞)

Assuming a sinusoidal time variation of flux:

$$\Phi = \Phi_m \sin(\omega t)$$ …………… (21)

the induced emfs:

$$e_1 = N_1 \frac{d\Phi}{dt} = N_1 \cdot \omega \cdot \Phi_m \cdot \cos(\omega t) = \sqrt{2} E_1 \cos(\omega t)$$ ……………. (22)

$$e_2 = N_2 \frac{d\Phi}{dt} = N_2 \cdot \omega \cdot \Phi_m \cdot \cos(\omega t) = \sqrt{2} E_2 \cos(\omega t)$$ ……………….(23)

The rms voltages in complex notation:

$$\underline{E}_1 = j4.44 f N_1 \Phi_m$$ ……………. (25)

$$\underline{E}_2 = j4.44 f N_2 \Phi_m$$ ……………(26)

The ratio of induced voltages:

$$\frac{e_1}{e_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = a$$ …………….. (27)

For an ideal transformer:

$V_1 = E_1$ and $V_2 = E_2$ …………… (28)

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$ ……………..(29)

There are no power losses and

$S1 = S2$ ………………(30)

$V_1 I_1 = V_2 I_2$ ……………… (31)

From the above equation:

$$\frac{V_1}{V_2} = \frac{I_1}{I_2} = a$$ …………….. (32)

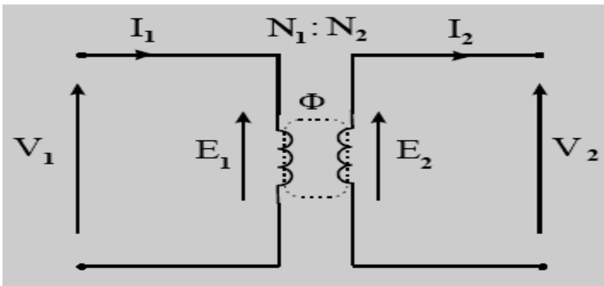


Fig.3.14 The equivalent circuit of ideal transformer with the magnetic link

To eliminate the magnetic connection let us express the secondary voltage and current as:

$$V_1 = aV_2 = V_2'$$ …………… (33)

$$I_1 = \frac{1}{a} I_2 = I_2'$$ ……………(34)

$V2'$ and $I2'$ are secondary voltage and current referred to a primary side.

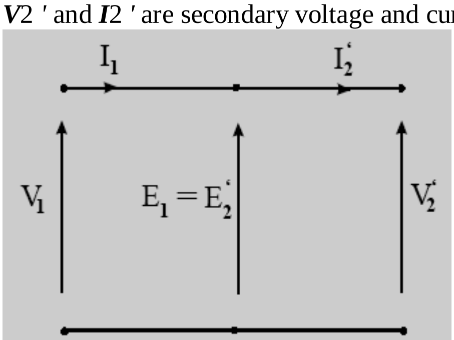


Fig.3.15 The equivalent circuit of an ideal transformer with electric connection of two Sides

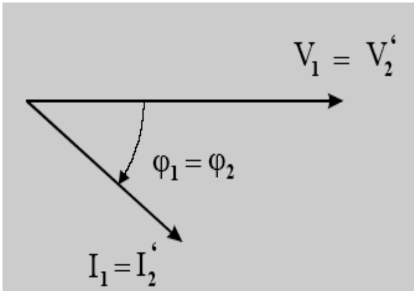


Fig.3.16 Phasor diagram for an ideal transformer

Transformer can be used for the impedance matching.

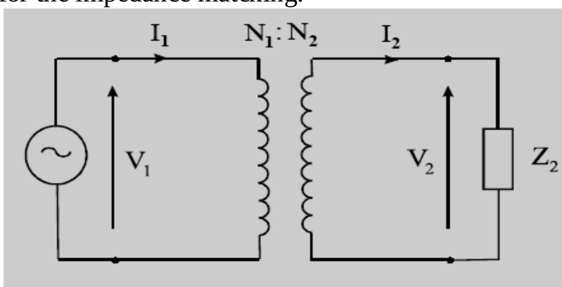


Fig.3.17 Ideal transformer with secondary load impedance

$$\frac{\boldsymbol{V}_1}{\boldsymbol{I}_1} = \frac{a\boldsymbol{V}_2}{\frac{\boldsymbol{I}_2}{a}} = a^2 \frac{\boldsymbol{V}_2}{\boldsymbol{I}_2} = a^2 \boldsymbol{Z}_2 = \boldsymbol{Z}_2' \qquad \text{………… (35)}$$

$\boldsymbol{Z}2\ '$ is the output impedance seen at the primary side or the transformer input impedance as shown in Fig.3.18.

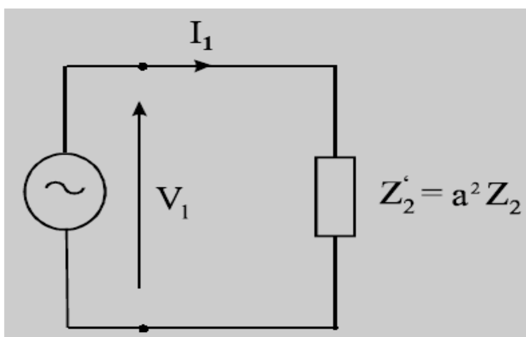


Fig.3.18. Input impedance for ideal transformer with secondary load impedance $\boldsymbol{Z}2$

3.2.3 A real transformer

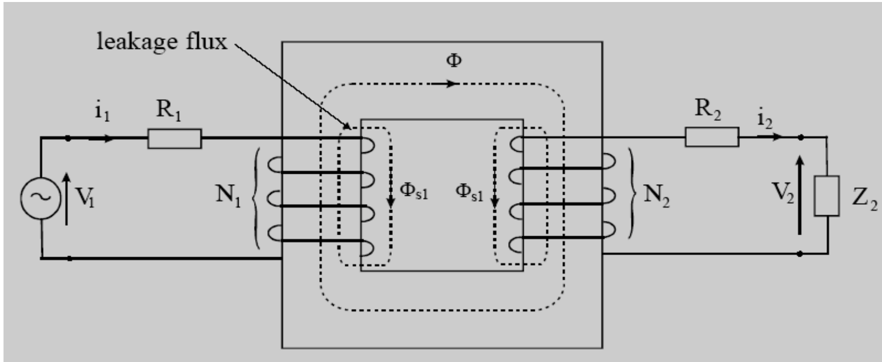


Fig.3.19 Circuit diagram of a real two winding transformer

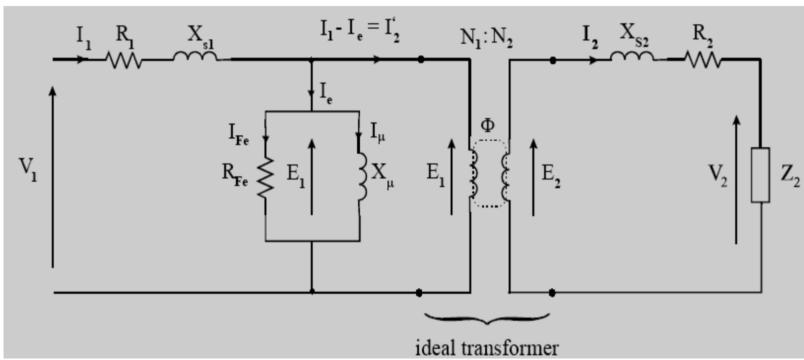


Fig.3.20 Equivalent circuit of the real transformer with magnetic coupling

Equation of magnetomotive forces in complex notation:

$$\underline{F}_{me} = \underline{F}_{m1} - \underline{F}_{m2} \qquad \text{………….(36)}$$

where ***Fme*** is the mmf responsible for generation of flux Φ. The above equation written in other form:

$$N_1 \underline{I}_e = N_1 \underline{I}_1 - N_2 \underline{I}_2 \qquad \text{…………. (37)}$$

Thus:

$$\underline{I}_e = \underline{I}_1 - \underline{I}_2 \frac{N_2}{N_1} \qquad \text{……………….(38)}$$

$$\underline{I}_e = \underline{I}_1 - \underline{I}_2' \qquad \text{……………. (39)}$$

where:

Ie **-** excitation current, and

I2

′ - secondary current referred to the primary side.

From the equivalent circuit in Fig.3.20

$$\underline{V}_1 = \underline{E}_1 + (R_1 + jX_{s1})\underline{I}_1 \qquad \text{……………..(41)}$$

$$\underline{V}_2 = \underline{E}_2 - (R_2 + jX_{s2})\underline{I}_2 \qquad \ldots\ldots\ldots\ldots\ldots(42)$$

Multiplying the above equation by *a*:

$$a \cdot \underline{V}_2 = a \cdot \underline{E}_2 - a^2 R_2 \frac{\underline{I}_2}{a} - ja^2 X_{s2} \frac{\underline{I}_2}{a} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(43)$$

or written in other form:

$$\underline{V}_2' = \underline{E}_2' - R_2' \underline{I}_2' - jX_{s2}' \underline{I}_2' \qquad \ldots\ldots\ldots\ldots\ldots(44)$$

where:

$\underline{V}_2' = a\underline{V}_2$,

$\underline{E}_2' = a\underline{E}_2$,

$\underline{I}_2' = \frac{\underline{I}_2}{a}$, Are the secondary voltages and current referred to the primary side

$R_2' = a^2 R_2$,

$X_{s2}' = a^2 X_{s2}$ Are the secondary circuit parameters referred to the primary side

$\underline{E}_2' = \underline{E}_1$ …………………. (Fig.3.21)

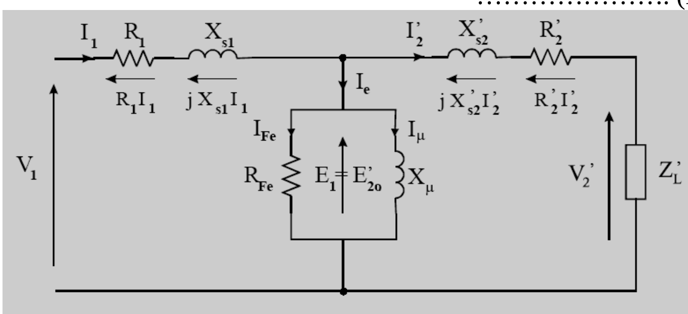


Fig.3.21 Modified equivalent circuit of a single-phase transformer

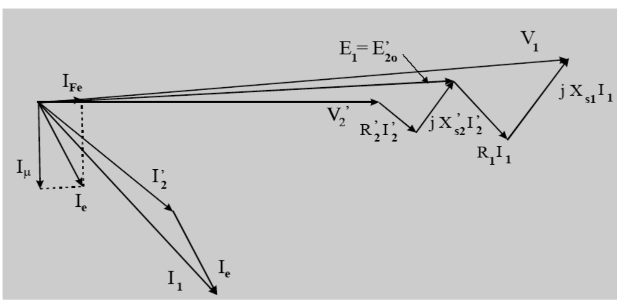


Fig.3.22 Phasor diagram of the real transformer at the inductive load (load current is lagging the voltage)

The primary impedance together with the shunt parameters can be transferred to the secondary side as shown in Fig.3.23.

The transferred to the secondary side parameters are as follows:

$$R_1' = \frac{R_1}{a^2}, \quad X_{s1}' = \frac{X_{s1}}{a^2}$$

$$R_{Fe}' = \frac{R_{Fe}}{a^2}, \quad X_\mu' = \frac{X_\mu}{a^2}$$

$$V_1' = \frac{V_1}{a}, \quad I_1' = aI_1.$$

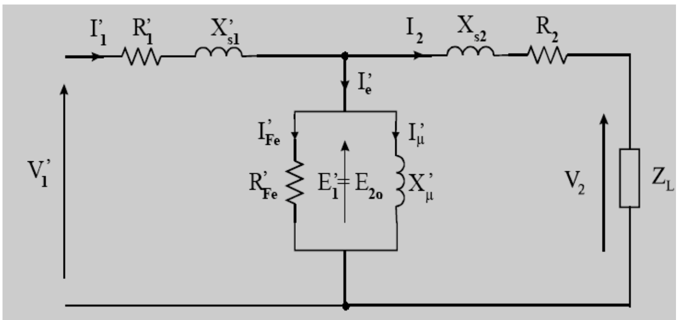


Fig.3.23 Equivalent circuit with parameters referred to the secondary side.

3.2.4 Test for determination of circuit parameters

3.2.4.1 Open-circuit test

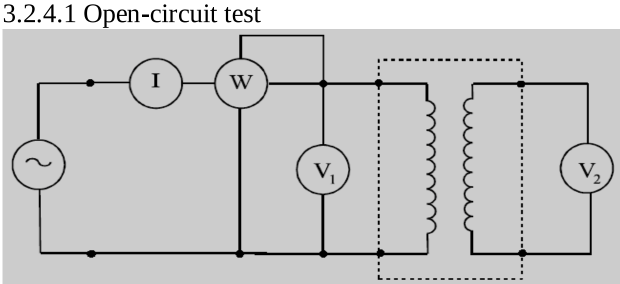


Fig.3.24 Circuit diagram for the open-circuit test of the transformer

Measured quantities:

V1 , ***Io***, ***Po*** and ***V***2.

Since ***I I o n*** << and ***R RFe*** 1 << , ***X X s***1 << µ the modified equivalent circuit is as shown in Fig.3.25. From the measured quantities the following parameters can be calculated:

$$P_o = \frac{E_1^2}{R_{Fe}} = \frac{V_1^2}{R_{Fe}} \qquad \text{……..(45)}$$

$$R_{Fe} = \frac{V_1^2}{P_o} \qquad \text{…….(46)}$$

$$X_\mu = \frac{E_1}{I_\mu} = \frac{V_1}{I_\mu} \qquad \text{……..(47)}$$

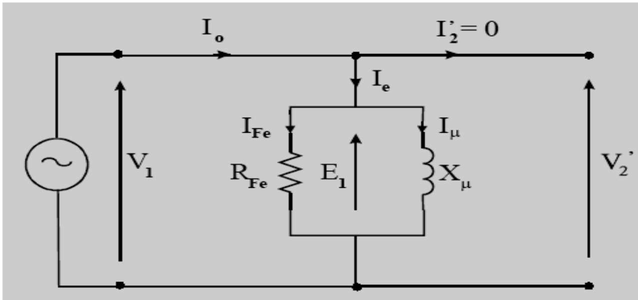


Fig.3.25 Equivalent circuit of the transformer at the open circuit test

According to the phasor diagram of Fig.3.26, which corresponds to the equivalent circuit of Fig.3.25, the magnetizing current:

$$I_\mu = \sqrt{I_o^2 - I_{Fe}^2} \qquad \text{………… (48)}$$

Where $I_{Fe} = \frac{P_o}{V_1}$

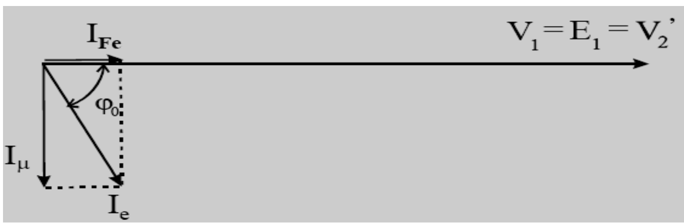
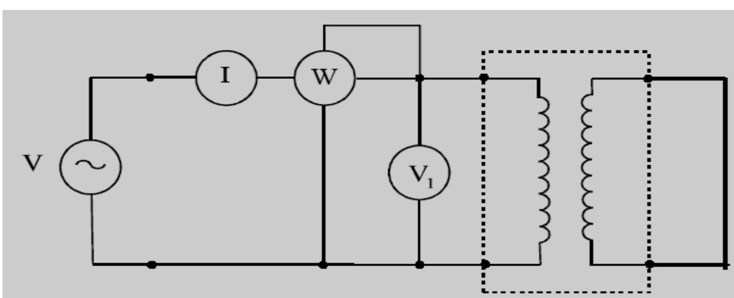


Fig.3.26 Phasor diagram at open-circuit test corresponding with the equivalent circuit in Fig.3.25.

From the open-circuit test: $a = \frac{V_1}{V_2}$

3.2.4.2 Short-circuit test



W Fig.3.27 Circuit diagram of the transformer at short-circuit test

Since ***Ie*** << ***I sc*** , the equivalent circuit is as in Fig.3.28.

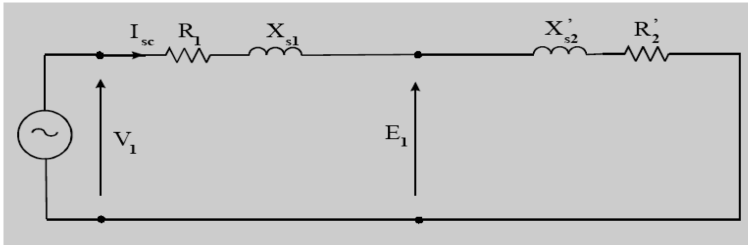


Fig.3.28 Equivalent circuit of the transformer at short circuit test

Measured quantities: ***V***1 , ***Isc*** , ***Psc***.

Since: $$\boldsymbol{P_{sc} = R_{sc} I_{sc}^2}$$ …………..(51)

the following parameters can be determined from the measured quantities:

$$\boldsymbol{R_{sc} = R_1 + R_2' = \frac{P_{sc}}{I_{sc}^2}}$$ ……….. (52)

Since $$\boldsymbol{Z_{sc} = \frac{V_{sc}}{I_{sc}}}$$ ……….. (53)

the short-circuit reactance is equal to

$$X_{sc} = X_{s1} + X_{s2}' = \sqrt{Z_{sc}^2 - R_{sc}^2}$$ …………..(54)

For most of power transformers:

$$R_1 = R_2' = \frac{R_{sc}}{2} \quad \text{and} \quad X_{s1} = X_{s2}' = \frac{X_{sc}}{2}$$ ……………(55)

The phasor diagram corresponding to the equivalent circuit in Fig.3.28 is drawn in Fig.3.29.

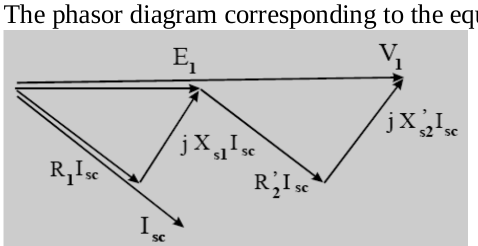


Fig.3.29 Phasor diagram at short-circuited secondary

3.2.6 Transformer operation at on-load condition

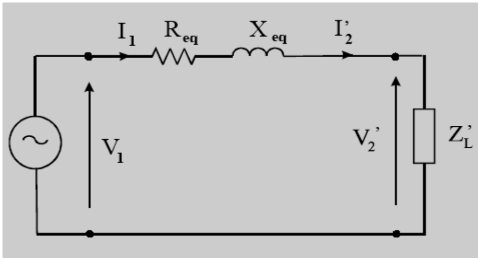


Fig.3.30 Simplified equivalent circuit of the transformer at on-load operation
(a)

(a) (b)

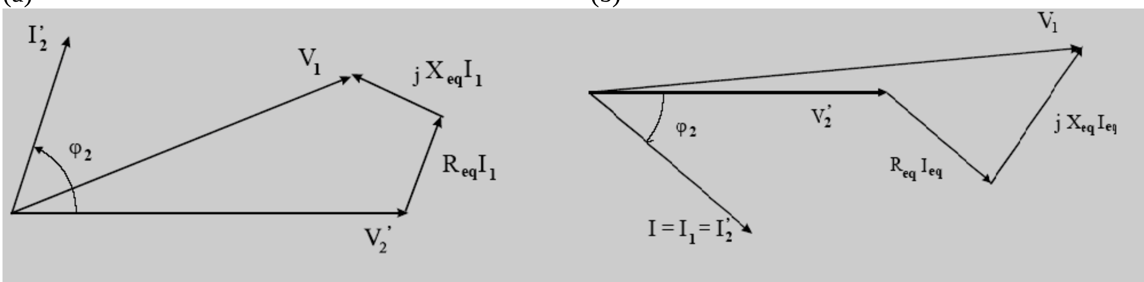


Fig.3.31 Phasor diagrams at on-load conditions: (a) capacitive load (b) inductive load,

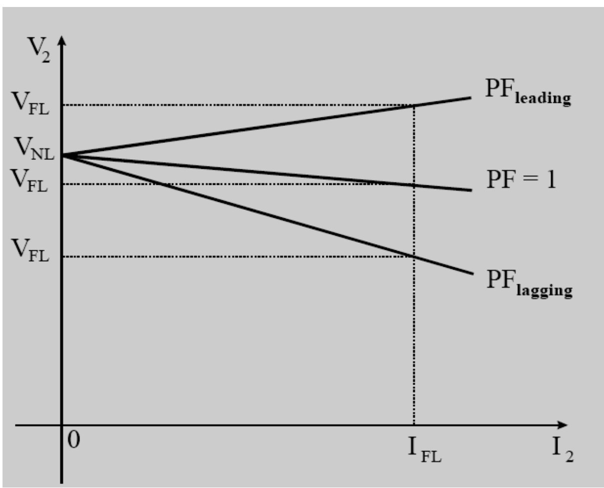


Fig.3.32 V-I characteristics (external characteristics) at ***V***1 = const, f=const, PF=const.

Voltage regulation

As the current is drawn trough transformer, the secondary voltage changes because of voltage drop in the internal impedance of the transformer. *Voltage regulation* (Δv%) is used to identify this characteristic of voltage change. It is defined as:

$$\Delta v_{\%} = \frac{|V_2|_{NL} - |V_2|_L}{|V_2|_L} 100\%$$

…………..(56)

Referring to the equivalent circuit shown in Fig.3.30 Equ.56 can also be written as:

$$\Delta v_{\%} = \frac{|V_2^{'}|_{NL} - |V_2^{'}|_L}{|V_2^{'}|_L}$$

The load voltage is normally taken as the rated voltage. Therefore:

$$|V_2^{'}|_L = |V_2^{'}|_{rated}$$

From equivalent circuit

$$V_1 = V_2^{'} + \mathrm{R}_{eq} I_2^{'} + jX_{eq} I_2^{'}$$

If the load is thrown off $(I_1 = I_2^{'} = 0)$, the voltage $V_1 = V_2^{'}$. hence

$$|V_2^{'}|_{NL} = |V_1|$$

Finally:

$$\Delta v_{\%} = \frac{|V_1| - |V_2^{'}|_{rated}}{|V_2^{'}|_{rated}} 100\%$$

…………(57)

The voltage regulation depends on power factor of the load. This can be appreciated from the phasor diagram (Fig.3.30). The locus of V1 is a circle of radius ' $|Z_{eq} I_1^{'}|$
The magnitude
of V1 will be maximum if the phasor ' $|Z_{eq} I_1^{'}|$ is in phase with V2. That is

$$\varphi_2 + \varphi_{eq} = 0, \text{ and } \varphi_2 = -\varphi_{eq}$$

where: φ2 is the angle of the load impedance, and

φeq is the angle of the transformer equivalent impedance Zeq.
Therefore the maximum voltage regulation occurs if the power factor angle of the load is the same as the transformer equivalent impedance angle and the load power factor is lagging.
To keep the output voltage unchanged i.e. to adjust it to the required value, turns ratio is changed by means of tap-changing switch as shown in Fig.3.33.

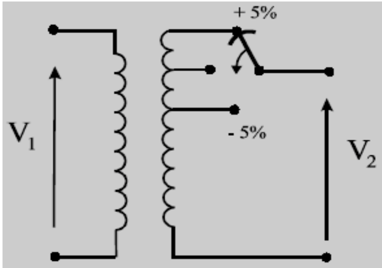


Fig.3.33 Tap changing switch to vary the secondary winding in the range of ±5% of the rating value

3.2.7 Efficiency

Definition:

$$\eta = \frac{P_2}{P_1}, \qquad \text{or} \qquad \eta_{\%} = \frac{P_2}{P_1} \cdot 100\% \qquad \text{………(58)}$$

where: ***P***1 and ***P***2 are the input and output powers respectively.
If expressed in terms of power losses:

$$\eta = \frac{P_2}{P_2 + \Delta P} \qquad \text{………….(59)}$$

The power losses consist of mainly the losses in the core ∆***PFe*** and in the winding ∆***Pw***

$$\Delta P = \Delta P_{Fe} + \Delta P_w \qquad \text{…………..(60)}$$

The latter one is equal to:

$$\Delta P_w = R_{sc} I_2^2 = \left(\frac{I_2}{I_{2n}}\right)^2 \Delta P_{wn} = I_{2pu}^2 \Delta P_{wn} \qquad \text{…………….(61)}$$

Since the output power is at 2 2*n V V* = :

$$P_2 = V_2 I_2 \cos\varphi_2 = V_{2n} I_{2n} \frac{I_2}{I_{2n}} \cos\varphi_2 = S_n I_{2pu} \cos\varphi_2 \qquad \text{…………(62)}$$

The transformer efficiency:

$$\eta = \frac{I_{2pu} S_n \cos\varphi_2}{I_{2pu} S_n \cos\varphi_2 + I_{2pu}^2 \Delta P_{wn} + \Delta P_{Fe}} \qquad \text{…………..(63)}$$

The efficiency vs. secondary current characteristic is shown in Fig.3.34. The maximum efficiency is when the iron losses are equal to cooper losses. It comes from

$$\frac{d(\eta)}{d(I_{2pu})} = 0 \qquad \text{…………..(64)}$$

at constant: ***Sn***, *cos* □2, ∆***Pwn*** and ∆***PFe*** the maximum efficiency is at:

$$\cos\varphi_2 = 1, \text{ and when } \quad I_{2pu}^2 \Delta P_{wn} = \Delta P_{Fe}$$

or expressed in other way $\Delta P_w = \Delta P_{Fe}$ ………..(65)

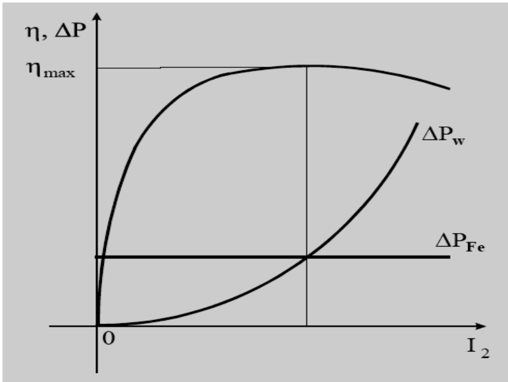


Fig.3.34 Efficiency and power losses versus secondary current characteristics

3.2.8 "Per unit" system

In "per unit" (pu) system all quantities and equivalent circuit parameters are expressed not in terms of normal units, but as a proportion of reference or rated value. This is particularly useful in the quantitative description of transformer work.

Let us select a reference value of the voltage equal to the rated value ***Vn***. Then the per unit value is

$$V_{1pu} = \frac{V_1}{V_{1n}}, \qquad V_{2pu} = \frac{V_2}{V_{2n}}$$ …………………..(66)

$$I_{1pu} = \frac{I_1}{I_{1n}}, \qquad I_{2pu} = \frac{I_2}{I_{2n}}$$ ………….(67)

If we take as the reference impedance defined as

$$Z_{1n} = \frac{V_{1n}}{I_{1n}}, \qquad Z_{2n} = \frac{V_{2n}}{I_{2n}}$$ …..……..(68)

then the expression

V= ***I. Z*** ……………(69)

in the real units can be written in per unit values as follows

$$\frac{V}{V_n} = \frac{I}{I_n}\frac{Z}{Z_n}$$ …………….(71)

We see that

$$Z_{pu} = \frac{V_{pu}}{I_{pu}} = Z\frac{I_n}{V_n}$$ ……………. (72)

The impedance of the windings of transformers and rotating machines is usually expressed as pu value and is related to the value in Ohms by the equation above.

Let us now consider the pu. system for power *P* or *S*. If the reference value of power

$$S_n = V_{1n} \cdot I_{1n} = V_{2n} I_{2n} \qquad \text{………………(73)}$$

$$S_{pu} = \frac{S}{S_n} = \frac{V \cdot I}{V_n I_n} = V_{pu} I_{pu} \qquad \text{……………….(74)}$$

Having all quantities of one side expressed in pu. system we do not have to transfer them to another side using turns ratio adjustment. They are just equal to the value of another side. For example:

$$\frac{V_{1pu}}{V_{2pu}} = \frac{V}{V_{1n}} \frac{V_{2n}}{V_2} = \frac{N_1}{N_2} \frac{N_2}{N_1} = 1 \qquad \text{………………(75)}$$

or

$$\frac{I_{1pu}}{I_{2pu}} = \frac{I_1}{I_{1n}} \frac{I_{2n}}{I_2} = \frac{N_2}{N_1} \frac{N_1}{N_2} = 1 \qquad \text{……………… (76)}$$

3.3 Three-phase transformers

3.3.1 Construction

(a)

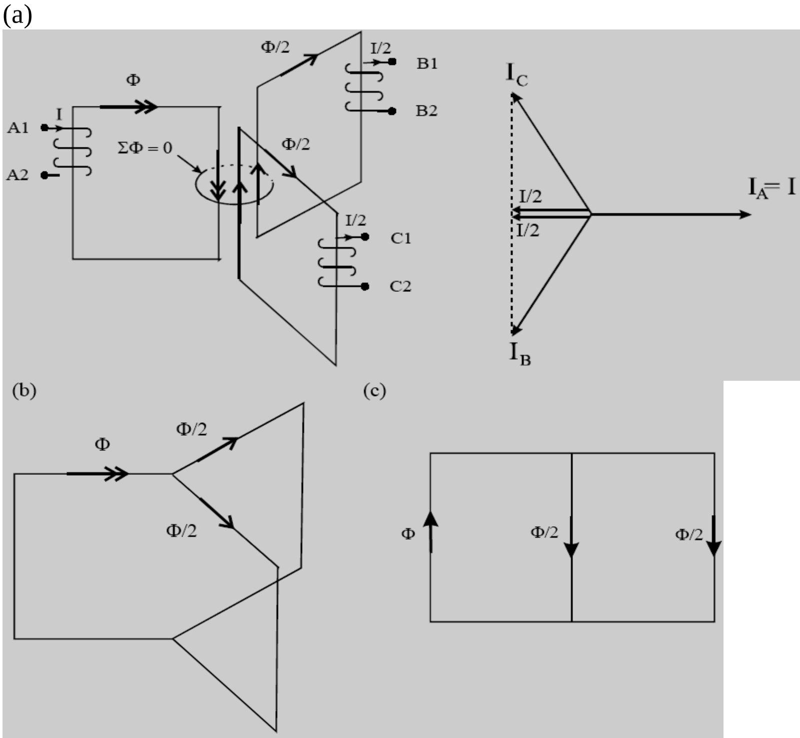


Fig.3.35.(a) Single-phase transformers supplied from 3-phase symmetrical source, (b) 3-phase transformer core with magnetic symmetry, (c) core of the real 3-phase coretype

transformer

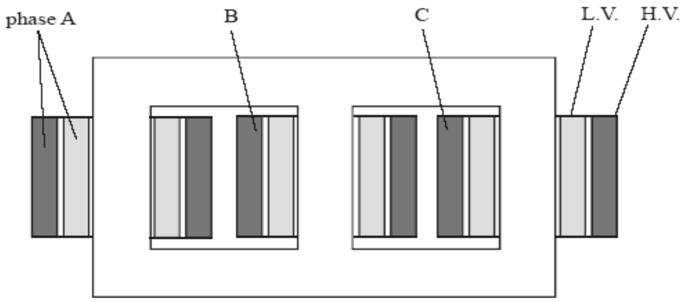
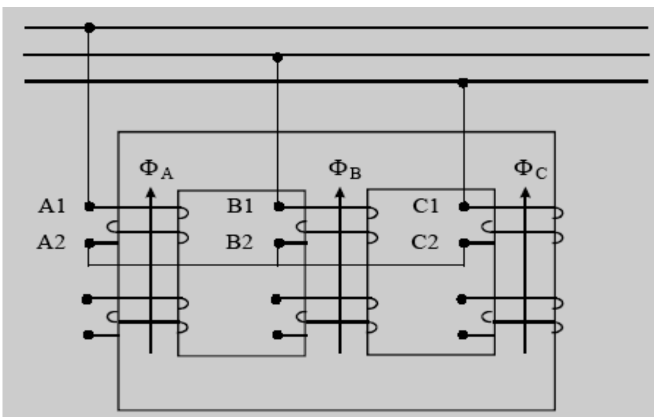
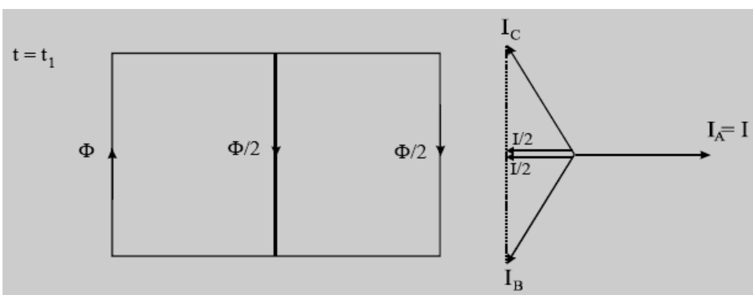


Fig.3.36 Three-phase core-type transformer





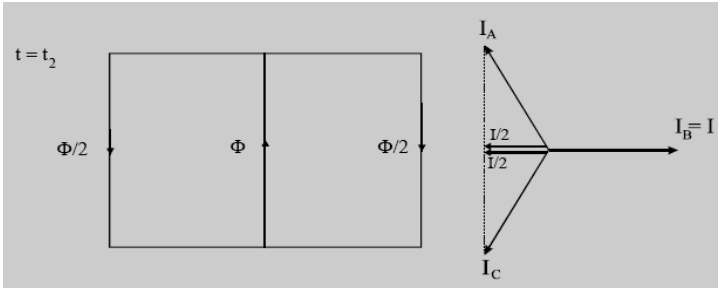
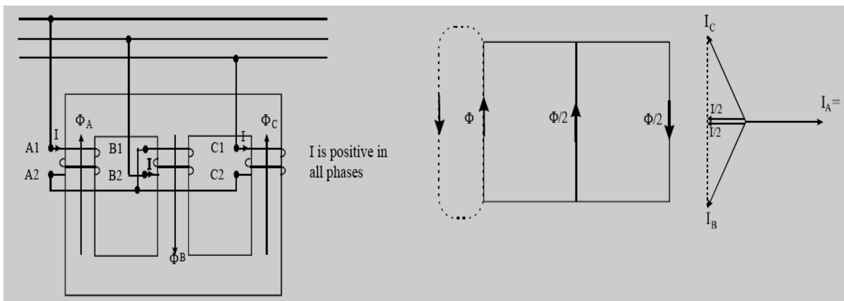
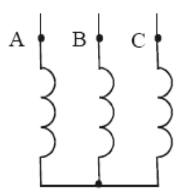
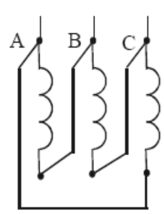


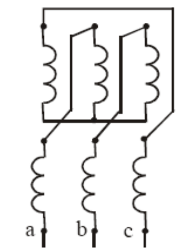
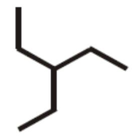
Fig.3.37 Winding connection of 3-phase transformer and flux distribution in the core legs



3.3.2 Connection groups of three-phase winding

Table 3.1 Connection of three- phase winding

Type of connection	Circuit diagram	Graphic symbol	Symbol	
			H.V.	L.V.
Star		Y	Y	y
Delta		Δ	D	d

Zigzag			-	z

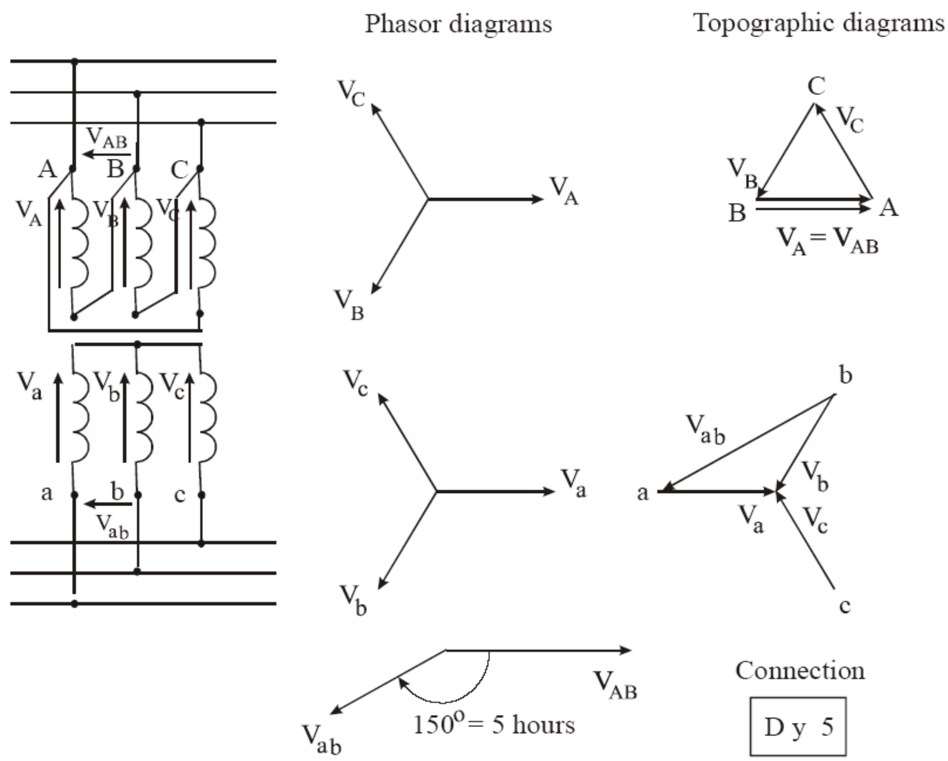


Fig.39. Three-phase transformer connected in $\boldsymbol{Dy_o}5$

3.3.3 Parallel operation of transformers

Demands put upon the operation of transformers connected in parallel, which must be fulfilled to avoid wrong operation at no-load and on-load conditions:

1.1 There must be no currents in the secondary windings at no-load conditions,

2.1 The transformers must load themselves accordingly to their rated powers at on-load Operation.

3.1 The phase angles of the secondary line currents of all in parallel connected transformers must be the same.

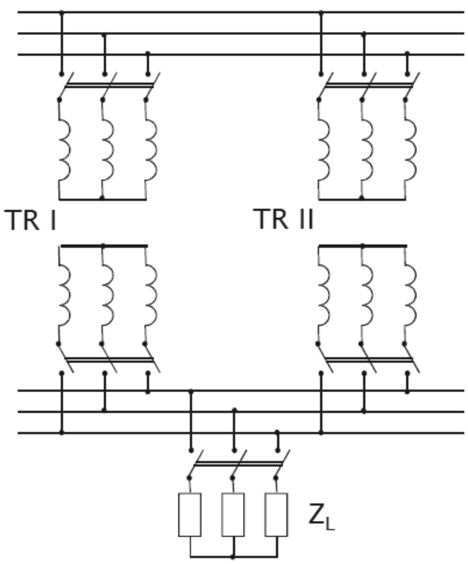


Fig.3.40 Three-phase transformers connected in parallel

To meet these demands the transformers must satisfy the following requirements:

1) Transformers must have the same voltage ratio,

2) The connection group of transformers must be identical,

3) The rated short-circuit voltages of transformers must be the same,

4) The ratio of rated powers (S^I / S^{II}) should not exceed 1/3.

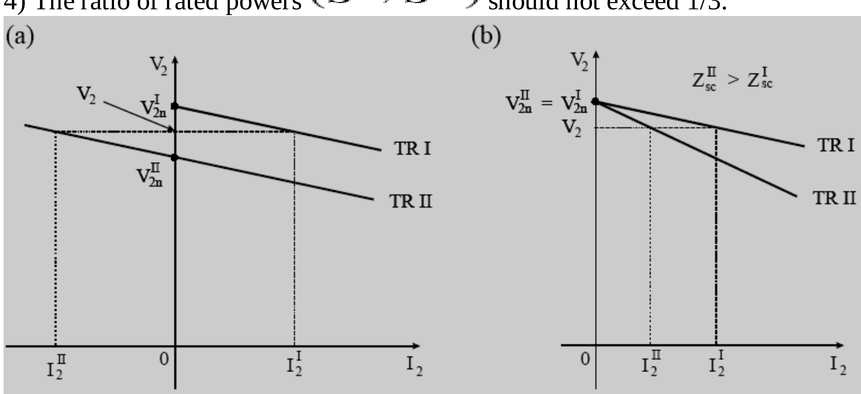


Fig.3.41.(a) and (b) Illustrations to the requirements 1) and 3) respectively

3.4 Auto-transformer

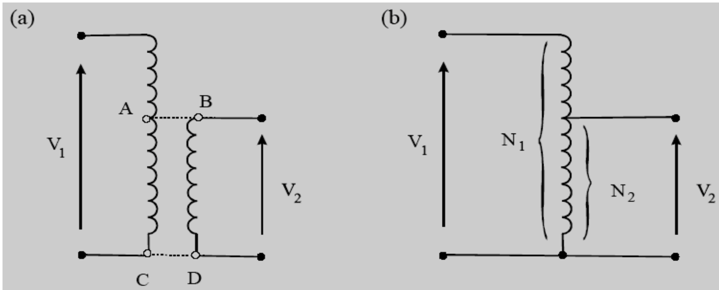


Fig.3.42 An explanation to the construction of auto-transformer

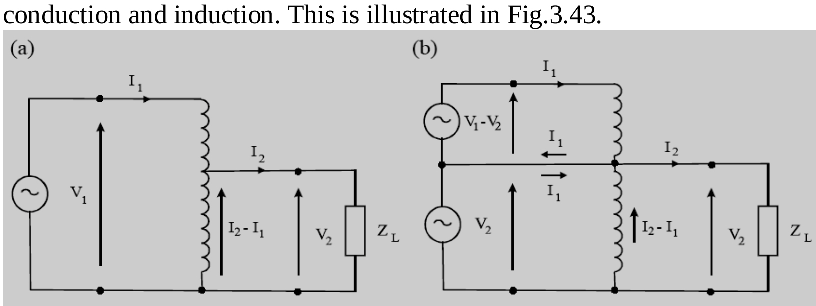
Similar, as for two-winding transformer the turn ratio is defined as follows:

$$a = \frac{N_1}{N_2} \qquad \ldots\ldots\ldots\ldots\ldots(77)$$

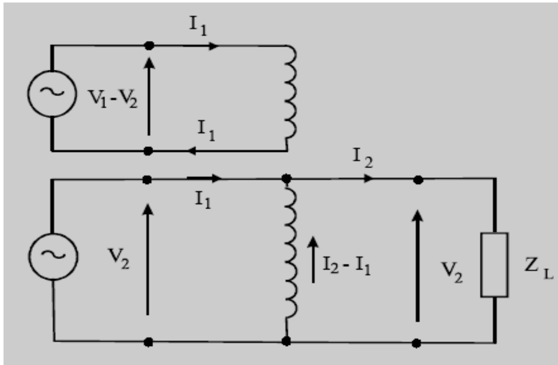
and it is approximately equal to the voltage ratio:

$$a \cong \frac{V_1}{V_2} \qquad \ldots\ldots\ldots\ldots\ldots(78)$$

The power is transferred from the primary side to the secondary side in two ways: by conduction and induction. This is illustrated in Fig.3.43.



(c)



(d)

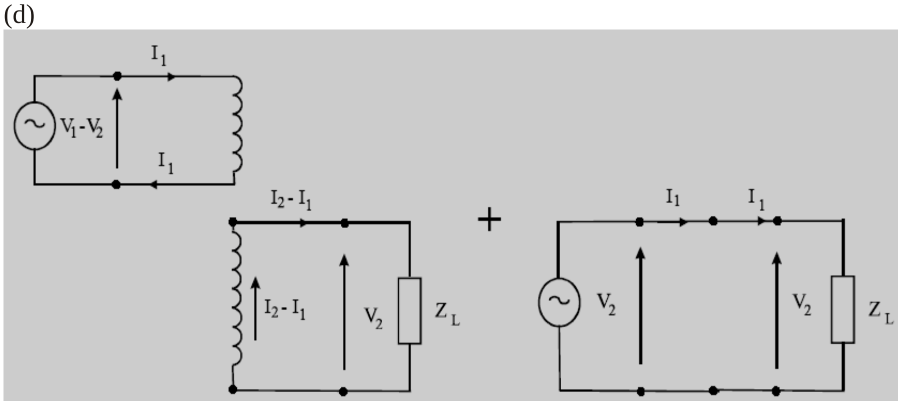


Fig.3.43 Explanation to the power transfer in the auto-transformer

Ignoring the power losses the total volt-ampere power is the sum of "conduction" power ***Sc*** and "induction" power ***Si***.

$$\boldsymbol{S} = \boldsymbol{S_i} + \boldsymbol{S_c} \qquad \text{……………(79)}$$

where:

$$\boldsymbol{S_i} = (V_1 - V_2)\boldsymbol{I_1} = V_1\boldsymbol{I_1}\left(1 - \frac{1}{\boldsymbol{a}}\right) \qquad \text{……………(80)}$$

$$\boldsymbol{S_c} = V_2\boldsymbol{I_1} = V_1\boldsymbol{I_1}\frac{1}{\boldsymbol{a}} \qquad \text{……………..(81)}$$

Since

$$\boldsymbol{S} = V_1\boldsymbol{I_1} \qquad \text{……………..(82)}$$

the two power components expressed in terms of the total power are:

$$S_i = S\left(1 - \frac{1}{a}\right) \quad \text{................(83)}$$

$$S_c = S\frac{1}{a} \quad \text{................(84)}$$

The sum:

$$S_i + S_c = S\left(1 - \frac{1}{a}\right) + S\frac{1}{a} = S \quad \text{...............(85)}$$

gives the total power *S*.
The common type of auto-transformer, which can be found in most of laboratories is the variable-ratio auto-transformer in which the secondary connection is movable as shown in Fig.3.44.

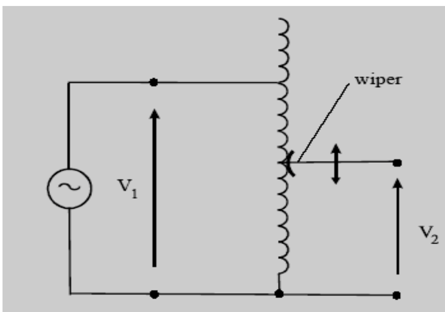


Fig.3.44 Auto-transformer with variable secondary voltage

Chapter-4

4 INSTRUMENT TRANSFORMERS

4.1 Introduction

Instrument transformers (ITs) are designed to transform: voltage (Voltage (VTs) or Potential Transformers (PTs)) or current (Current transformers (CTs)) from the high values in the transmission and distribution systems to the low values that can be utilized by low voltage current metering devices.

There are three primary applications for which ITs are used:
- metering (for energy billing and transaction purposes)
- protection control (for system protection and protective relaying purposes)
- load survey (for economic management of industrial loads)

Depending on the requirements for those applications, the IT design and construction can be quite different. Generally, the metering Its require high accuracy in the range of normal operating voltage and current. Protection ITs require linearity in a wide range of voltages and currents. During the disturbance, such as a system fault or over voltage transients, the output of the IT is used by a protective relay to initiate an appropriate action (open or close a breaker, reconfigure the system, etc.) to mitigate the disturbance and protect the rest of the power system. Instrument transformers are the most common and economic way to detect a disturbance. Typical output levels of instrument transformers are 0-5 A and 115-120 V for CTs and VTs, respectively. There are several classes of accuracy for instrument transformers defined by the IEEE, CSA, IEC and ANSI standards. Figure 1 presents a conceptual design of CTs and VTs.

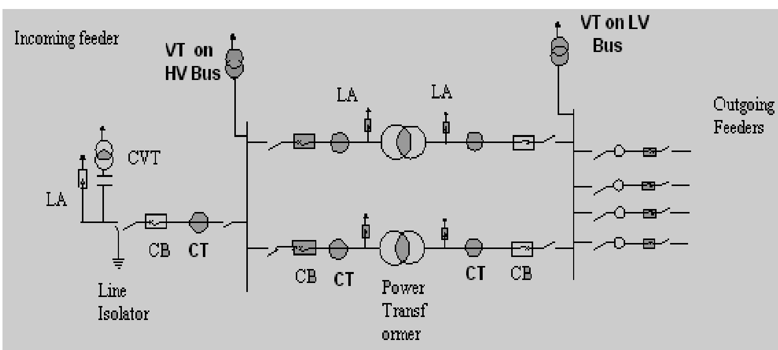


Fig.4.1 Position of CTs and VTs. In a Substation

4.2 Current transformers

A current transformer is designed to provide a current in its secondary which is accurately proportional to the current flowing in its primary.
Care must be taken that the secondary of a current transformer is not disconnected from its load while current is flowing in the primary as in this circumstance a very high voltage would be produced across the secondary. Current transformers are often constructed with a single primary turn either as an insulated cable passing through a toroidal core, or else as a bar to which circuit conductors are connected.

Design
For a current transformer design, the core characteristics must be carefully selected because excitation current I_e essentially subtracts from the metered current and affects the ratio and phase angle of the output current.

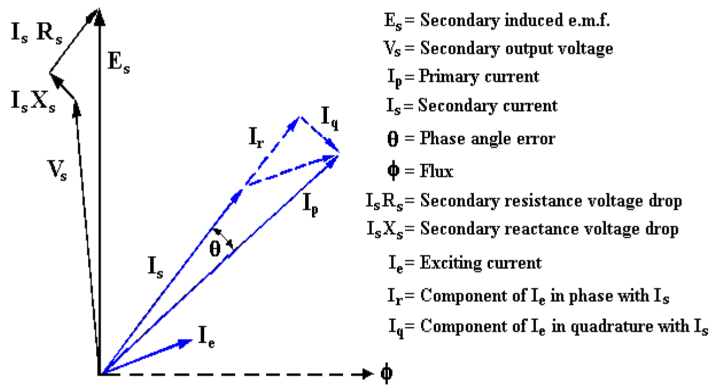


Fig.4.2 The higher the exciting current or core loss the larger the error

4.3 Measuring and protective current transformers

Measuring current transformer

Permeability of the core material high and core loss low reduces exciting current ,low exciting current reduces (I_{fe}<<) current error . The exciting current determines the maximum accuracy that can be achieved with a current transformer

Protective current transformer

Permeability of the core material is low ,When remanence is reduced to a lower level (increase the useful flux density, gapping), the voltage spikes produced by the leakage inductance due to the transformer saturation will be eliminated. In linear current transformers there are generally air gaps in the iron core to reduce the time constant and remanence. Such current transformers are used only to protect objects of major importance that require a short tripping time.

4.4 Selecting core material

When choosing a core material a reasonable value for B_m (0,2 ... 0,3 T) typically results in L_c and R_{fe} values large enough to reduce the current flowing in these elements so as to satisfy the ratio and phase requirements.

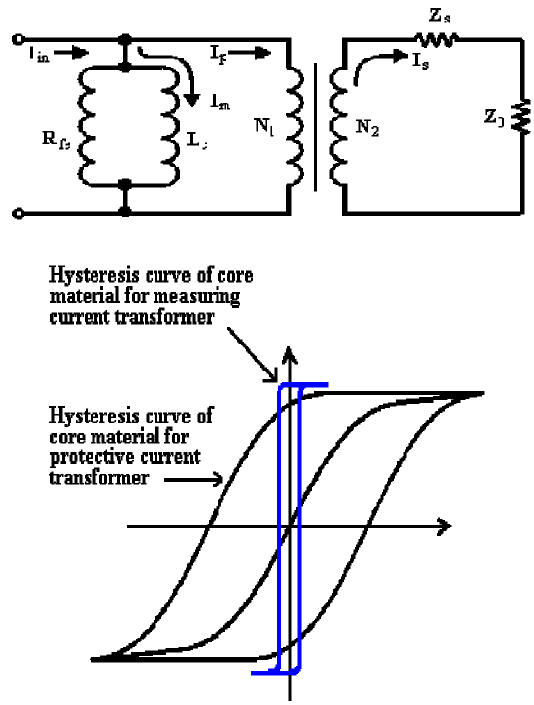


Fig.4.3. A transformer intended to supply measuring instruments, meters, relays and other similar apparatus

Effect of Gapping

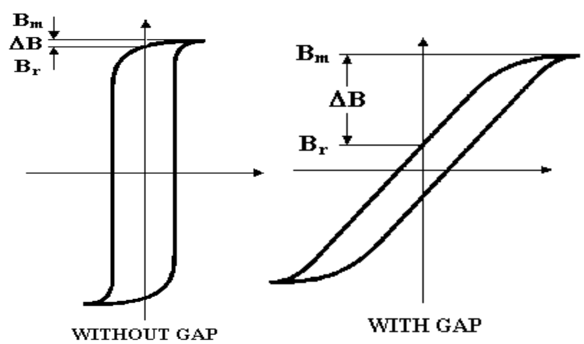


Fig.4.4 Effective length of the magnetic path

Air gap increases the effective length of the magnetic path

Air-gapped current transformers

These are auxiliary current transformers in which a small air gap is included in the core to produce a secondary voltage output proportional in magnitude to current in the primary winding. Sometimes termed ´transactors´ or ´quadrature current transformers´, this form of current transformer has been used as an auxiliary component of unit protection schemes in which the outputs into multiple secondary circuits must remain linear for and proportioned to the widest practical range of input currents.

Anti-remanence current transformers

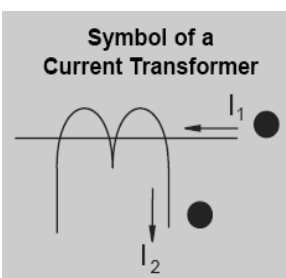
A variation in the overdimensioned class of current transformer has small gap(s) in the core magnetic circuit, thus reducing the possible remanent flux from approximately 90% of saturation value to some 10% only. These gap(s) are quite small, for example 0.12mm total, and so within the core saturation limits. Errors in current transformation are thereby significantly reduced when compared with those with the gapless type of core.

Linear current transformers

The ´linear´ current transformer constitutes an even more radial departure from the normal solid core CT in that it incorporates an appreciable air cap, for example 7.5-10mm. As its name implies the magnetic behaviour tends to linearization by the inclusion of this gap in the magnetic circuit. However, the purpose of introducing more reluctance into the magnetic circuit is to reduce the value of magnetizing reactance, this in turn reduces the secondary time-constant of the CT thereby reducing the overdimensioning factor necessary for faithful transformation.

The time constant $\tau_c$of the circuit depends on the inductance of the coil and on the resistance in the circuit in accordance to the following simple formula:

$$\tau_c = \frac{L}{R}$$



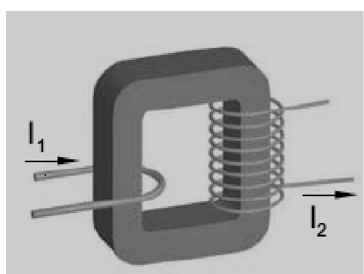
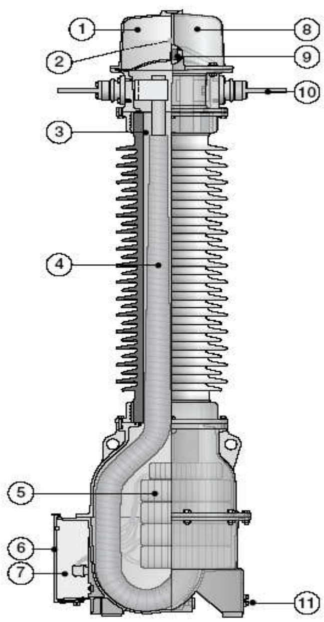


Fig.4.5 Current Transformer symbol and winding layout

4.5 Connection of a CT

The object with current transformers is to transform current ratios rather than voltage ratios. Current ratios are the inverse of voltage ratios. The thing to remember about transformers is that Pout = (Pin — transformer power losses). With this in mind, let's assume we had an ideal loss-less transformer in which Pout = Pin. Since power is voltage times current, this product must be the same on the output as it is on the input. This implies that a 1:10 step-up transformer with the voltage stepped up by a factor of 10 results in an output current reduced by a factor of 10. This is what happens on a current transformer. If a transformer had a one-turn primary and a ten-turn secondary, each amp in the primary results in 0.1A in the secondary, or a 10:1 current ratio. It's exactly the inverse of the voltage ratio — preserving volt times current product.

If we want to produce an output on the secondary proportional to the primary current, this output is usually in volts output per amp of primary current. The device that monitors this output voltage can be calibrated to produce the desired results when the voltage reaches a specified level.



A burden resistor connected across the secondary produces an output voltage proportional to the resistor value, based on the amount of current flowing through it. With our 1:10 turns ratio transformer that produces a 10:1 current ratio, a burden resistor can be selected to produce the voltage we want.

1. Gas cushion
2. Oil filling unit (hidden)
3. Quartz filling
4. Paper-insulated primary conductor
5. Cores/secondary windings
6. Secondary terminal box
7. Capacitive voltage tap (on request)
8. Expansion vessel
9. Oil sight glass
10. Primary terminal
11. Ground terminal

If 1A on the primary produces 0.1A on the secondary, then by Ohm's law, 0.1 times is the ratio
With this knowledge, the user can choose the burden resistor to produce their desired output voltage.

Fig.4.6. showing the internal view of a C.T

The output current of 0.1A for a 1A primary on the 1:10 turns ratio transformer will produce 0.1 V/A across a 1Ω burden resistor, 1V per amp across a 10Ω burden and 10V per amp across a 100Ω burden resistor.

When choosing the burden resistor, the engineer can create any output voltage per amp, as long as it doesn't saturate the core. Core saturation level is an important consideration when specifying current transformers. The maximum volt-microsecond product specifies what the core can handle without saturating. The burden resistor is one of the factors controlling the output voltage. There's a limit to the amount of voltage that can be achieved at a given frequency. Since frequency = 1/cycle period, if the frequency is too low (cycle period too long) so that voltage-time product exceeds the core's flux capacity, saturation will occur. The flux that exists in a core is proportional to the voltage times cycle period. Most specifications provide a maximum volt-microsecond product that the current transformer can provide across the burden resistor. Exceeding this voltage with too large a burden resistor will saturate the transformer and limit the voltage.

What happens if the burden resistor is left off or opens during operation? The output voltage will rise trying to develop current until it reaches the saturation voltage of the coil at that frequency. At that point, the voltage will cease to rise and the transformer will add no additional impedance to the driving current. Therefore, without a burden resistor, the output voltage of a current transformer will be its saturation voltage at the operating frequency.

There are factors in the current transformer that affect efficiency. For complete accuracy, the output current must be the input current divided by the turns ratio. Unfortunately, not all the current is transferred. Some of the current isn't transformed to the secondary, but is instead shunted by the inductance of the transformer and the core loss resistance. Generally, it's the inductance of the transformer that contributes the majority of the current shunting that detracts from the output current. This is why it's important to use a high-permeability core to achieve the maximum inductance and minimize the inductance current. Accurate turns ratio must be maintained to produce the expected secondary current and the expected accuracy. the current transformed is smaller than the input current by:

$$\mathbf{I_{TRANSFORMED}=I_{INPUT}-I_{CORE}-jI_{MAG}\ (1)}$$

What about the effect the transformer will have on the current it's monitoring? This is where the term burden enters the picture. Any measuring device alters the circuit in which it measures. For instance, connecting a voltmeter to a circuit causes the voltage to change from what it was before the meter was attached. However minuscule this effect may or may not be, the voltage you read isn't the voltage that existed before attaching the meter. This is also true with a current transformer. The burden resistor on the secondary is reflected to the primary by (1/N2), which provides a resistance in series with the current on the primary. This usually has minimal effect and is usually only important when you are concerned about the current that would exist when the transformer isn't in the circuit, such as when it's used as a temporary measuring device.

loss components in the circuit. The resistance of the primary loop, the core loss resistance, the secondary is reduced by 1/N2, and the secondary burden resistor RBURDEN is also reduced by a factor of N2. These are losses that affect current source (I). The resistances have an indirect effect on the current transformer accuracy. It's their effect on the circuit that they are monitoring that alters its current. The primary dc resistance (PRIdcr) and the secondary DCR/N2 (RDCR/N2) don't detract from the Iinput that is read or is affecting the accuracy of the actual current reading. Rather, they alter the current from what it would be if the current transformer weren't in the circuit.

4.6 Construction of a Current Transformer

Primary Winding :The primary winding consists of one or more parallel conductor of aluminum or copper designed as a U-shaped bushing with voltage grading capacitor layers. The insulation technique is automated to give a simple and controlled wrapping, which improves quality and minimizes variations. The conductor is insulated with a special paper with high mechanical and dielectric strength, low dielectric losses and good resistance to ageing. This design is also very suitable for primary windings with many primary turns. This is used when the primary current is low, for instance unbalance protection in capacitor banks. (Ex. ratio 5/5A)

Cores and Secondary Windings

current transformers are can normally accommodate any core configuration required.
Cores for metering purposes are usually made of nickel alloy, which features low losses (= high accuracy) and low saturation levels. The protection cores are made of high-grade oriented steel strip. Protection cores with air gaps can be supplied for special applications. The secondary winding consists of double enameled copper wire, evenly distributed around the whole periphery of the core. The leakage reactance in the winding and also between extra tapping is therefore negligible.

Impregnation

Heating in a vacuum dries the windings. After assembly all free space in the transformer (app. 60%) is filled with clean and dry quartz grain. The assembled transformer is vacuum-treated and impregnated with degassed mineral oil. The transformer is always delivered oil-filled and hermetically sealed.

Tank and Insulator

The lower section of the transformer consists of an aluminum tank in which the secondary windings and cores are mounted. The insulator, mounted above the transformer tank, consists as standard of high-grade brown-glazed porcelain. Designs using light gray porcelain or silicon rubber can be quoted on request.
The sealing system consists of O-ring gaskets.

Currents The rated currents are the values of primary and secondary currents on which performance is based
Rated Primary Current Should be selected about 10 - 40% higher than the estimated operating current. Closest standardized value should be chosen.
Extended Current Ratings : A factor that multiplied by the rated current gives the maximum continuous load current and the limit for accuracy. Standard values of extended primary current are 120, 150 and 200% of rated current. Unless otherwise specified, the rated continuous thermal current shall be the rated primary current.
Rated Secondary Current :The standard values are 1, 2 and 5 A. 1 A is chosen for low measuring and protection burdens. 1 A also gives an overall lower burden requirement through lower cable burden.
Rated Short-time Thermal Current (Ith) Ith depends on the short-circuit power and can be calculated from the formula: $Ith = Pk / Um \times \sqrt{3}$ kA. Standardized duration of Ith is 1 second. Other duration (3 sec.)
must be specified.
Reconnection The current transformer can be designed with either primary or secondary reconnection or a combination of both to obtain more current ratios.

Primary Reconnection The ampere-turns always remain the same and thereby the load capacity (burden) remains the same. The short-circuit capacity however is reduced for the lower ratios.

Secondary Reconnection Extra secondary terminals (taps) are taken out from the secondary winding. The load capacity drops as the ampere-turns decrease on the taps, but the short-circuit capacity remains constant. Each core can be individually reconnected.
Burden and Accuracy Class (IEC) Burden Accuracy Rct
Instrument Security Factor (FS)
Accuracy Limit Factor (ALF) The external impedance in the secondary circuit in ohms at the specified power factor. It is usually expressed as the apparent power – in VA -, which is taken up at rated secondary current. It is important to determine the power consumption of connected meters and relays including the cables. Unnecessary high burdens are often specified for modern equipment.
Note that the accuracy for the measuring core, according to IEC, can be outside the class limit if the actual burden is below 25% of the rated burden.
The accuracy class for measuring cores is according to the IEC standard given as 0.2, 0.5 or 1.0 depending on the application. For protection cores the class is normally 5P
or 10P. Other classes are quoted on request, e.g. class PX, TPX or TPY. The secondary winding resistance at 75 deg C
To protect meters and instruments from being damaged by high currents, an FS factor of 5 or 10 often is specified for measuring cores. This means that the secondary current
will increase a maximum of 5 or 10 times when the rated burden is connected. FS10 is normally sufficient for modern meters.
The protection cores must be able to reproduce the fault current without being saturated. The overcurrent factor for protection cores is called ALF. ALF = 10 or 20 is commonly used. Both FS and ALF are valid at rated burden only.

4.7 Standard Burdens for Current Transformers with

The errors in ratio and phase angle depend on the impedance connected to the secondary of the transformer. This impedance is commonly referred to as “burden”. The calculations required for determining the performance of a transformer when different burdens are applied are beyond the scope of this discussion.
Therefore, the standard burdens as outlined in IEEE C57.13 are used to represent typical service conditions. Each transformer is rated according to its performance at these standard burdens.
Many current transformers supply only a limited number of watt-hour meter elements with a limited number of runs. For metering and relaying applications, IEEE C57.13 has established the standard burdens as given in Table Below

Table 4.1

Standard Burdens for Current Transformers with 5 A Secondaries					
Burden Designation	**Resistance (∅)**	**Inductance (mH)**	**Impedance (∅)**	**Volt Amperes (at 5 A)**	**Power Factor**
		Metering Burdens			
B-0.1	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5	0.45	0.58	0.5	12.5	0.9
B-0.9	0.81	1.04	0.9	22.5	0.9
B-1.8	1.62	2.08	1.8	45.0	0.9
		Relaying Burdens			
B-1	0.50	2.3	1.0	25.0	0.5

B-2	1.00	4.6	2.0	50.0	0.5
B-4	2.00	9.2	4.0	100.0	0.5
B-8	4.00	18.4	8.0	200.0	0.5

Actual Burdens for Current Transformers

Actual devices connected to instrument transformers often include an inductor with an iron core, which usually means that the inductance is not constant but varies during the cycle, and varies differently with different currents. Exact analysis of current transformer performance with such devices is difficult. Fortunately, the impedances of most instruments and meters are sufficiently constant that no appreciable error is introduced by considering them to be constant. Many electro-mechanical relays, however, have variable impedance. Analysis of the transformer performance is usually based on an equivalent value at normal current. This can be justified on the basis that the burden at higher current is usually less and thus the current transformer will perform better than expected from the equivalent burden.

Current Transformers: Accuracy Classes for Relaying

Relaying accuracy classes for CTs are defined with a “C” or a “T” classification.

“C” indicates that the transformer ratio can be calculated. These are transformers which are constructed so that the effect of leakage fluxes on its performance are negligible.

“T” indicates the transformer where the leakage flux has an appreciable effect on the ratio. Since the calculation of the excitation current by-passed is a tedious process, the performance of the transformer can only be determined by test. The basis for classification of performance for relaying is an error limit of 10% at any current from 1.0 to 20 times normal. The accuracy class is the description of how much voltage the

transformer can supply to the output circuit (burden), without the CT core going into saturation.

For example, a transformer that can supply a 2 ohm output circuit (burden) at 100 A [20 times normal current (5 A)] or 200 V, without saturating the core and within a 10% error limit, is classified as 200 accuracy class. Refer to Figure 2. Standard accuracy classes, which may be assigned for a relaying current transformer, are 50, 100, 200, and 800. If a C200 transformer can supply 100 A secondary output at exactly 10% error into a 2 ohm burden, then the exciting branch is not over 10 amperes. If the current is lower, then the burden can be higher without exceeding the output voltage limit if a transformer can carry 2 ohms at 50 amperes and deliver 200 volts.

However, if the burden is 1 ohm at 200 amperes, it will not work since the internal impedance will be significant in relation to the 1 ohm burden.

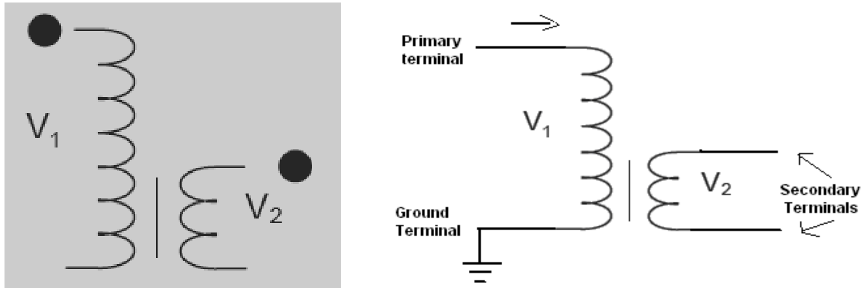
4.8 Voltage Transformers

Voltage or potential transformers are used to transform High Voltages AC to low (120 V AC) accurately for measurement and relaying in an Electrical network.

Two types of voltage transformer are used for protective-relaying purposes, as follows:

(1) the "instrument potential transformer," hereafter to be called simply "potential transformer," and (2) the "capacitance potential device." A potential transformer is a conventional transformer having primary and secondary windings. The primary winding is connected directly to the power circuit either between two phases or between one phase and ground, depending on the rating of the transformer and on the requirements of the application. A capacitance potential device is a voltage-transforming equipment using a

capacitance voltage divider connected between phase and ground of a power circuit.



Symbol of a V T

Fig.4.7. Symbol and winding layout of a VT

ACCURACY OF POTENTIALTRANSFORMERS

The ratio and phase-angle inaccuracies of any standard ASA accuracy class1 of potential transformer are so small that they may be neglected for protective-relaying purposes if the burden is within the "thermal" volt-ampere rating of the transformer. This thermal volt-ampere rating corresponds to the full-load rating of a power transformer. It is higher than the volt-ampere rating used to classify potential transformers as to accuracy for metering purposes. Based on the thermal volt-ampere rating, the equivalent-circuit impedances of potential transformers are comparable to those of distribution transformers.

Burden

The "burden" is the total external volt-ampere load on the secondary at rated secondary voltage. Where several loads are connected in parallel, it is usually sufficiently accurate to add their individual volt-amperes arithmetically to determine the total volt-ampere burden.
If a potential transformer has acceptable accuracy at its rated voltage, it is suitable over the range from zero to 110% of rated less voltage. Operation in excess of 10% overvoltage may cause increased errors and excessive heating.
Where precise accuracy data are required, they can be obtained from ratio-correctionfactor curves and phase-angle-correction curves supplied by the manufacturer.

RATED BURDENS OF A VT

The rated burden of a secondary winding of a capacitance potential device is specified in watts at rated secondary voltage when rated phase-to-ground voltage is impressed across the capacitance voltage divider. The rated burden of the device is the sum of the watt burdens that may be impressed on both secondary windings simultaneously.
Adjustment capacitors are provided in the device for connecting in parallel with the burden on one secondary winding to correct the total-burden power factor to unity or slightly leading.

Table 4.2

Rated Circuit Voltage , kv		Rated Burden, watts
Phase-to-Phase	Phase-to-Ground	
115	66.4	25
138	79.7	35

161	93.0	45
230	133.0	80
287	166.0	100

The rated burden of coupling-capacitor potential devices is 150 watts for any of the rated circuit voltages, including those of Table 4.2.

CAPACITANCE POTENTIAL DEVICES (Capacitive voltage Transformer)
Two types of capacitance potential device are used for protective relaying: (1) the "coupling-capacitor potential device," and (2) the "bushing potential device." The two devices are basically alike, the principal difference being in the type of capacitance voltage

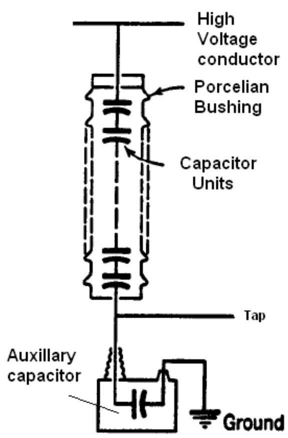


Fig.4.7. Coupling-capacitor voltage divider

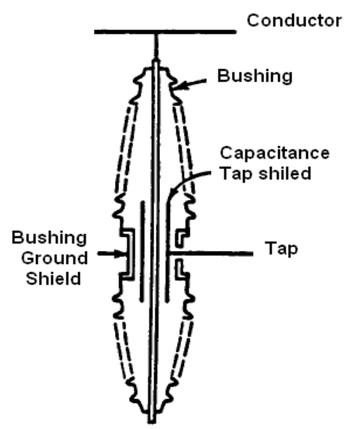
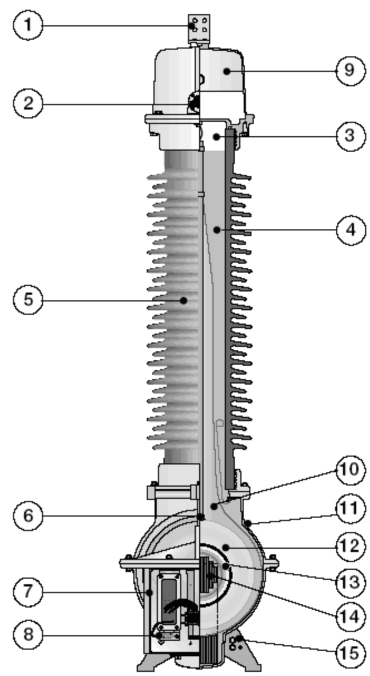


Fig. 2 Capacitance-bushing voltage divider.

1. Primary terminal
2. Oil level indicator
3. Oil
4. Quartz filling
5. Insulator
6. Lifting lug
7. Secondary terminal box
8. Neutral end terminal
9. Expansion system
10. Paper insulation
11. Tank
12. Primary winding
13. Secondary windings
14. Core
15. Ground connection



Two types of capacitance potential device are used for protective relaying: (1) the "coupling-capacitor potential device," and (2) the "bushing potential device." The two devices are basically alike, the principal difference being in the type of capacitance voltage divider used, which in turn affects their rated burden. The coupling-capacitor device uses as a voltage divider a "coupling capacitor" consisting of a stack of series-connected capacitor units, and an "auxiliary capacitor," as shown schematically in Fig. 1. The
bushing device uses the capacitance coupling of a specially constructed bushing of a circuit breaker or power transformer, as shown schematically in Fig. 2. .
Both of these relaying potential devices are called "Class A" devices.2 They are also sometimes called "In-phase" or "Resonant" devices 3 for reasons that will be evident later. Other types of potential devices, called "Class C" or "Out-of-phase" or "Non-resonant," are also described in References 2 and 3, but they are not generally suitable for protective relaying, and therefore they will not be considered further here.

4.9 Standard Burdens for Voltage Transformers

The standard burdens to be used for testing and comparing voltage transformers are rated at 120 volts and at 69.3 volts. IEEE C57.13 specifies that the 120 volt-rated burden will be used for any transformer with the secondary voltage in the range of 115 to 120 volts, while the 69.3 volt burden will be used for any
transformer with the secondary voltage in the range of 65 to 72 volts. This means that the actual volt amperes in the burden in a given test may be different than the nominal value of the burden in volt amperes. For instance, if the standard burden is 25 volt amperes, the actual burden when it is used for testing a transformer with 115 volt secondary is $(115/120)^2$ or .918 times the nominal value of 25.

Table 4.3

Standard Burdens for Voltage Transformers					
	Burden Designation	Volt Amperes	Power Factor	Burden Impedance 120 V Burden	69.3 V Burden
Burdens	W	12.5	0.10	1152	384
	X	25	0.70	576	192
	M	35	0.20	411	137
	Y	75	0.85	192	64
	Z	200	0.85	72	24
	ZZ	400	0.85	36	12

The burdens rated 69.3 volts have an impedance only one-third of that of burdens rated 120 volts and they should not be used in testing or rating transformers rated at 115 to 120 volts. Transformers rated at 115 or 120 volts should be treated as 115 or 120 volt transformers, and if they are actually used at reduced voltage, the performance will not be different if the 120 volt burden is used as a basis for performance. This is
because the performance of a transformer down to voltages of about 5% of its rating is not significantly different from the performance at 100% voltage.
Table 4.3 gives the standard burdens for voltage transformers as outlined in IEEE C57.13.

The Broken-Delta Burden and The Winding Burden Condition in a PT
The broken-delta burden is usually composed of the voltage-polarizing coils of ground directional relays. Each relay's voltage-coil circuit contains a series capacitor to make the relay have a lagging angle of maximum torque. Consequently, the voltage-coil circuit has a leading power factor. The volt-ampere burden of each relay is expressed by the manufacturer in terms of the rated voltage of the relay. The broken-delta burden must be expressed in terms of the rated voltage of the potential-device winding or the tapped portion of the winding-whichever is used for making up the broken-delta connection. If the relay- and winding-voltage ratings are the same, the broken-delta burden is the sum of the relay burdens. If the voltage ratings are different, we must re-express the relay burdens in terms of the voltage rating of the broken-delta winding before adding them, remembering that the volt-ampere burden will vary as the square of the voltage, assuming no saturation.

The actual volt-ampere burdens imposed on the individual windings comprising the broken-delta connection are highly variable and are only indirectly related to the broken-delta burden. Normally, the three winding voltages add vectorially to zero. Therefore, no current flows in the circuit, and the burden on any of the windings is zero. When ground faults occur, the voltage that appears across the broken-delta burden corresponds to 3 times the zero-phase-sequence component of any one of the three phase-to-ground voltages at the potential-device location. We shall call this voltage "$3V_0$ ". What the actual magnitude of this voltage is depends on how solidly the system neutrals are grounded, on the location of the fault with respect to the potential device in question, and on the

configuration of the transmission circuits so far as it affects the magnitude of the zerophase- sequence reactance. For faults at the potential-device location, for which the voltage is highest, $3V_0$ can vary approximately from 1 to 3 times the rated voltage of each of the broken-delta windings. (This voltage can go even higher in an ungrounded-neutral system should a state of ferroresonance exist, but this possibility is not considered here because it must not be permitted to exist.) If we assume no magnetic saturation in the burden, its maximum current magnitude will vary with the voltage over a 1 to 3 range.

The burden current flows through the three broken-delta windings in series. As shown in Fig. 5, the current is at a different phase angle with respect to each of the winding voltages. Since a ground fault can occur on any phase, the positions of any of the voltages of Fig. 5 relative to the burden current can be interchanged. Consequently, the burden on each winding may have a wide variety of characteristics under different circumstances.
Another peculiarity of the broken-delta burden is that the load is really carried by the windings of the unfaulted phases, and that the voltages of these windings do not vary in direct proportion to the voltage across the broken-delta burden. The voltages of the unfaulted-phase windings are not nearly as variable as the broken-delta-burden voltage.

The winding voltages of the unfaulted phases vary from approximately rated voltage to $\sqrt{3}$ times rated, while the broken-delta-burden voltage, and hence the current, is varying from less than rated to approximately 3 times rated.

4.10 Construction of a Voltage Transformer

Primary Windings
The primary winding is designed as a multilayer coil of double enameled wire with layer insulation of special paper. Both ends of the windings are connected to metal shields.

Secondary and Tertiary Windings
In its standard design the transformer has a secondary measurement winding and a tertiary winding for ground fault protection, but other configurations are available as required. (2 secondary windings in a design) The windings are designed with double enameled wire and are insulated from the core and the primary winding with pressboard (presspahn) and paper. The windings can be equipped with additional terminals for other ratios (taps).

Core
The transformer has a core of carefully selected material, to give a flat magnetization curve. The core is over-dimensioned with a very low flux at operating voltage.

Impregnation
Heating in a vacuum dries the windings. After assembly, all free space in the transformer (approximately 60%) is filled with clean and dry quartz grains. The assembled transformer is vacuum-treated and impregnated with degassed mineral oil. The transformer is always delivered oil-filled and hermetically sealed.

Tank and Insulator
The lower section of the transformer consists of an aluminum tank in which the winding and core are placed. The tank consists of selected aluminum alloys that give a high degree of resistance to corrosion, without the need of extra protection. Anodized details can be offered on request. The sealing system consists of O-ring gaskets. The insulator, in its standard design, consists of high quality, brown glazed porcelain. The voltage transformers can also be constructed with silicone rubber insulators.

Inductive Voltage Transformer
Inductive voltage transformers are used for connection between phase and ground in networks with insulated or direct-grounded neutral points.
The transformers are designed with a low flux density in the core

5 TRANSFORMER BUSHINGS & SURGE ARRESTOR

A bushing is an electrical engineering component that allows a high voltage conductor to pass safely through an earthed metal wall or casing. Bushings appear on switchgear, transformers, circuit breakers and most other high voltage equipment. The bushing is hollow, allowing a conductor to pass along its centre and connect at both ends to other equipment
Some of the higher voltage types are called capacitor bushings because they form a low value capacitor between the conductor and the wall. This is done in order to carefully grade the reduce the electrical field stress that would otherwise occur and cause breakdown. Bushings do sometimes fail due to partial discharge degradation in the insulation. There is at present great interest in the electricity supply industry in monitoring the condition of high voltage bushings.

most high voltage bushings produced were capacitance graded, paper insulated, oil impregnated condensers with the capacitance layers provided by aluminum foil. This method of construction had provided the a very reliable bushing with excellent cost advantages over other types of construction. The only drawback to this type of construction was the time it took to impregnate the condenser. With cylinders of aluminum inside the condenser it can impregnate the paper insulation from the bottom of the condenser.

5.1 Bushing design theory

The basic theory of bushing design is to bring the potential through the tank of the transformer. This is accomplished by using two basic bushing design concepts; non-graded bushings and capacitance graded bushings. The former is the simplest concept as well as the oldest, known as bulk type bushings, as shown in figure 1. Capacitance graded bushings are available in four technologies. Resin bonded paper (RB) bushings, oil impregnated paper (OIP) bushings, resin impregnated paper (RIP) bushings and epoxy-resin impregnated paper (ERIP) bushings.

Condenser Type Design
The bushing is built up around a central conductor tube or rod on which the condenser body is wound. The upper and lower insulators, mounting flange, flange extension, spring assembly, sight bowl, lower support and clamping nut form an oil tight shell to contain the condenser and insulating oil. The sealing between components is accomplished with oil-resistant "O-rings" in grooves and/or oil-resistant flat fiber reinforced gaskets. The space between the shell and the condenser is filled with high-grade transformer oil. This oil is part of the insulating and cooling systems of the bushing. Above the oil, there is a gas space to provide for thermal expansion of the oil. The gas space is filled with dehydrated nitrogen gas. The oil level in the bushing can be monitored by visual inspection of the sight bowl. The sight bowl is prismatic to enhance observation of the oil level. The mounting flange and flange extension are high strength
corrosion-resistant aluminum. The lower support is designed to accept a variety of optional terminating devices such as standard threaded studs, or draw rod system.
The upper insulator is a one-piece high quality porcelain with sheds designed for maximum performance.

Designed to be used at angles of up to 60 deg from the vertical position A typical condenser type bushing for a 220 KV transformer

5.2 Construction of a Transformer bushing

The primary metal used in the housing is aluminum in the form of castings for flanges, heads and external ground sleeves.The other major housing components are the outboard and inboard insulators. these insulators have been porcelain but, today a number of viable alternatives are now being offered. The major alternative for the outboard

porcelain insulator is an insulator that is a composite of a resin-impregnated fiberglass and silicone rubber commonly called Silicone Rubber Insulators (SRI). Epoxy-resin materials are also being successfully applied as replacements for the

Condenser Core Winding : The High Quality Insulating paper is wound on Aluminium Tube for Currents upto 1250 Amps) / on copper Rod for Current Ratings of 2000 Amps / 3150 Amps. The winding machine has close looped controls to ensure consistency of winding parameters such as tension, pressure & temperature. At predecided locations by the winding program, precisely cut Aluminium Foils are inserted to achieve the uniform condenser grading. During the winding process partial drying of the paper Insulation is achieved.

Drying & Impregnation : The Condenser Cores are then completely dried and impregnated in Vacuum Drying Chambers in various stages such as Air Heating, Rough Vacuum, Fine Vacuum. The Level of Fine Vacuum is a critical parameter of Effectiveness of Drying. The Drying cycles are concluded based on Quality of Fine Vacuum measured on Pirani Gauges.

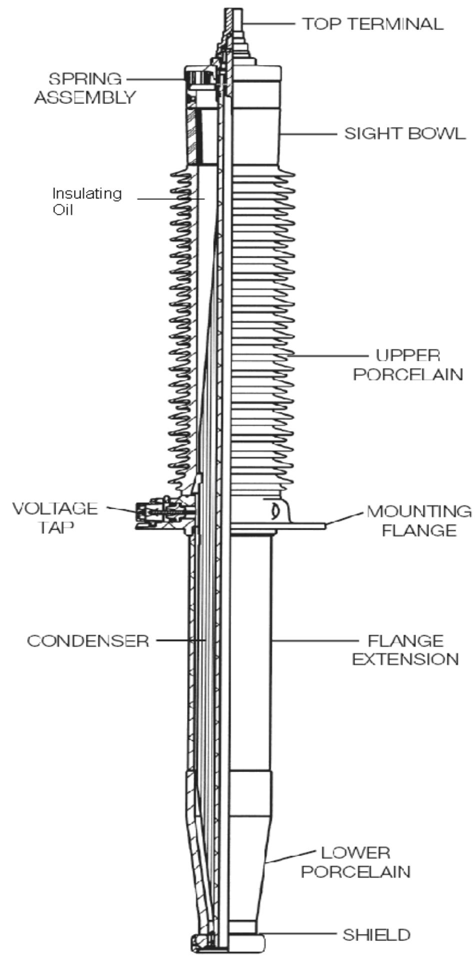


Fig.5.1 Bushing details

After the drying cycle is concluded, the oil impregnation is carried out at a predetermined rate of flow of Oil Inlet which is in relation with the Capillary Rise of the Paper Insulation.

Assembly : The Impregnated Condenser Cores are then assembled with the assembly components such as Air End Porcelain Insulator, Oil End Epoxy Insulator etc. The Entire Assembly is a Tie Rod Assembly with the "O" Rings used at all sealing locations. The Assembly is held together by a Pre Loaded Coil Spring Stack which ensures perfect sealing at highest operating temperatures & also supports the assembly against the Loads applied at HV Terminal. Gravity Die Cast Aluminium

Conservator & Mounting Flanges are used on the Bushing assembly. For Bushings upto 1250 Amps Aluminium Cast Electrodes with external surface painted with Polyurethane (PU) Paint are used which forms an integral part of the assembly. An extra tapped hole is provided on the Mounting Flange for fixing the substation earth flat. Self Earthing type Test Tap / Capacitance & Tan Delta Measurement Tap & Oil Filling, Sampling Valves are provided at Mounting flange Level.

Oil Flooding under Vacuum : The Fully Assembled & Leaktested Bushing is then filled with High Dielectric Strength Oil under Vacuum at Room Temperature for predecided duration & fine vacuum level.

Primary Terminations : The Primary Terminations are of Draw Lead Type for Current ratings upto 800 Amps & they are of Draw Rod Type for Current Ratings upto 1200 Amps with Cable Joint at Mounting Flange Level. The Primary Terminals are manufactured from Copper Alloys. For 2000 Amps & 3150 Amps current ratings.

Capacitance Graded Bushings

Figure 4 outlines the basic principles of capacitance graded bushings.Capacitance grading provides two basic design features with the ability to produce smaller diameter bushings. Without capacitance grading a 230 kV Class bushing may have to be nearly 6 feet in diameter. This smaller diameter, in turn, allows bushings to achieve higher voltage levels. Capacitance grading is available in two common types; non-fine grading and fine grading. Fine grading is used primarily for transformer bushings while non-fine grading is commonly used in bushings insulated with SF6 such as breakers and GIS.

RB Bushings

Resin Bonded (RB) paper bushings, were first developed by Emil Haefely in 1918 and are still used today up to 69 kV class. RB bushings utilize paper that is coated with resin and once the active part is wound it is placed in an oven to cure. RB bushings have high partial discharge levels and power factor. RB bushings do not use oil.

OIP Bushings

Oil Impregnated Paper (OIP) bushings were developed in the 1920’s. OIP bushings utilize kraft paper with layers of foil wound over a tube or conductor and then impregnated with transformer oil. Good OIP bushings are partial discharge free and have very low power factors. OIP bushings have a temperature operating range of -50°C to +105°C.

RIP Bushings

Resin Impregnated Paper (RIP) bushings were developed in Europe in the early 1950’s. RIP bushings utilize kraft paper with layers of foil wound over a conductor and vacuum impregnated with resin in a mold. RIP bushings use a small amount of transformer oil as an insulator and are generally higher in partial discharge and power factor than OIP bushings. RIP bushings have a limited temperature operating range of -30°C to +95°C.

ERIP Bushings

Epoxy-Resin Impregnated Paper (ERIP) bushings were developed in the 1980’s as an improvement on the RIP technology. ERIP bushings are made similar to RIP bushings and have similar power factors and partial discharge levels. ERIP bushings do not use transformer oil and are considered DRY bushings. ERIP bushings have higher temperature limits up to +120°C.

5.3 Voltage and BIL

Bushings are commonly classified with the transformer's three-phase voltage rating. This is known as the Voltage Class. However, bushings are single-phase devices and therefore, the voltage class rating of a bushing is somewhat immaterial to the selection process. The maximum line to ground voltage rating is the key information needed when selecting bushings.
Example of this are the 161 kV and 230 kV Class bushings. Both of these bushings have a maximum line to ground rating of 146 kV and therefore both can be applied to a 230 kV class transformer. However, this leads to the consideration of the BIL (Basic Insulation Level) of the bushing. The rule of thumb is that the bushing's BIL must be equal to or greater than the BIL of the transformer winding it is connected to. In the above example, the 161 kV class bushing has a BIL of 750 kV and the 230 kV class bushing's BIL is 900 kV. If the 230 kV class transformer's winding was rated 800 kV BIL you would not select the 161 kV class bushing for the application but rather the 230 kV class bushing.

Table 1 lists the voltage class, maximum line to ground voltage rating and BIL for the most common IEEE Standard bushings used today.

Table 5.1 Voltage class, maximum line to ground voltage rating and BIL

Voltage Class	**Line – Ground**	**BIL**	**Voltage Class**	**Line – Ground**	**BIL**
KV	**KV**	**KV**	**KV**	**KV**	**KV**
25	16	150	161	146	750
34.5	22	200	230	146	900
46	29	250	345	220	1175
69	44	350	500	318	1675
115	88	550	765	485	2050
138	102	650			

Current Ratings
Selecting a bushing with a current rating that will not limit the loadability or overloadability of the power transformer is one of the most important aspects of bushing selection. It is important to know that paper insulated bushings do not use thermally upgraded kraft paper like modern power transformers. The thermal basis of rating requirements is based on a 55 K rise transformer application., caution should be exercised when selecting the current rating of the bushing. The transformer's overload requirements must be known at the time of bushing selection.
Bushings selected with a current rating of 120% of the rated current of the transformer winding are considered to be able to withstand the overload requirements of IEEE Standard C57.12.00. Certain bushing designs are capable of withstanding greater overloads than other designs. As an example, bushings designed for draw lead application with the draw lead conductor supplied by the bushing manufacturer are capable of operating 15% above the nameplate rating without being overloaded. Whenever unusual overload requirements are required, consult with your bushing supplier.

5.4 Bushing Storage

All stored bushings should be periodically inspected. This inspection would look for chipped porcelains, damaged rain shields on non porcelain bushings, oil leaks, missing hardware, etc. This inspection is for obvious problems that would prevent the bushing from being serviceable.

It is recommended that the bushing manufacturer be consulted concerning bushing storage. They will provide instructions as to the proper storage of their bushing. Improper storage can result in not only damaging the bushing but also the equipment it is installed in.
The type of bushing and expected storage time should both be considered when determining storage options. If the bushings are to be stored outdoors the crates need to be of a weatherproof material or protected with an external covering. Knowledge of bushing construction is helpful in developing storage plans. If the bushing has an oil filled condenser the bushing should be stored such that the condenser remains covered. Bushing terminals should be checked to be tight and cap taps should be covered and filled with fluids as required. This is to prevent corrosion and water intrusion during storage. In all cases the goal should be to cause no damage to the bushing and keep it in good operating condition. If the bushings are subject to periodic testing the storage facility should be arranged such that this can be accomplished.

5.5 Surge Arrestors

Lightning imposes voltage surges on aerial lines either by direct strokes or by induction.
Such surges can be transmitted to underground lines. Opening and closing circuits in large generating plants or switching stations can raise voltages to two or three times normal for a brief period of time. In addition, excessive voltages and currents can result from short-circuit conditions when line-to-line or line-to-ground faults occur, because of inductive/capacitive characteristics of the line between the electric power source and the fault location. Transformer ferroresonance can create overvoltages
Since voltage surges can result in personnel injuries from electrical shock, insulation damage to equipment, and possibly fire
Surge arresters divert the effects of extremely short-term overvoltages on an electrical system to ground
Lightning arresters are made up of varistors whose resistance reduces as the implied voltage increases. This reduction in resistance continues until the lightning arrester acts just like a direct short to ground. Upon reaching this condition, the lightning energy diverts to ground away from the protected equipment, thus reducing the effect of the overvoltage they must be designed so as not to earth non-distructive voltage rises which are within limits.
The selection of a surge arrester rating is a balance between providing the lowest possible let through voltage (best protection), and the ability of the arrester to survive temporary overvoltages. Simplistically, the arrester is selected as the lowest available rating which will survive the expected temporary overvoltages under normal and abnormal system conditions.
Surge arresters are of the valve-type or the metal-oxide-varistor type shown in Fig 1. Gapless, metal-oxide arresters are preferred because of their better operating characteristics. Surge arresters are used to safeguard apparatus against hazards caused by abnormally high voltage surges. Such overvoltage can cause serious damage if arresters are not correctly coordinated with the insulation strength of the protected equipment, and are unable to discharge the energy properly. To function correctly, arrester protective levels must be lower than the insulation withstand strength of equipment to be protected.
Surge arrester protective margins
Impulse sparkover voltage. Impulse sparkover voltage is the highest value of voltage attained by an impulse of a designated wave shape and polarity applied across the terminals of an arrester prior to the flow of discharge current. This voltage plus the lead length voltage contribution is the highest that can be impressed on protected equipment because, at this level, the arrester will sparkover and discharge the surge to ground. Arrester surge wave sparkover voltage will be compared to the insulation lightning impulse (chopped-wave) crest value that the protected equipment is required to withstand for purposes of determining the protective margin.

Discharge voltage. Discharge voltage is the voltage that appears across the terminals of an arrester during passage of discharge current. Arrester maximum discharge voltage will be compared to the BIL value that the protected equipment is required to withstand for purposes of determining the protective margin.
Impulse protective level. For a defined waveshape, the impulse protective level is the higher of the maximum sparkover value or the corresponding discharge voltage value.

Duty cycle rating. The silicon carbide and MOV arrester have a duty cycle rating (in kV), which duty cycle testing established. This testing subjects an arrester to an AC rms voltage equal to its rating for 24 min, during which the arrester must withstand lightning surges at 1-min intervals. The magnitude of the surges is 10kA (10,000A) for station class arresters and 5kA for intermediate and distribution class arresters. The surge waveshape is an 8/20, which means the current wave reaches a crest in 8 ms (8 microseconds or 0.000008 sec) and diminishes to half the crest value in 20 ms.
Maximum continuous operating voltage rating (MCOV). The MCOV rating is usually 80% to 90% of the duty cycle rating. Table 2 lists the MCOV ratings of various MOV arresters.
The MCOV rating of an MOV arrester is important because it's the recommended magnitude limit of continuously applied voltage. If you operate the arrester at a voltage level greater than its MCOV, the metal oxide elements will operate at a higher-than-recommended temperature. This may lead to premature failure or shortened life

Silicon carbide LAs. This design uses nonlinear resistors made of a bonded silicon carbide placed in series with gaps. The function of the gaps is to isolate the resistors from the normal steady-state system voltage. One major drawback is the gaps require elaborate designs to ensure a consistent spark-over level and positive clearing (resealing) after a surge passes. This design has lost popularity due to the emergence of the MOV arrester.

MOV LAs. The MOV design usually does not require series gaps to isolate the elements from the steady-state voltages because the material (zinc oxide) is more nonlinear than silicon carbide. This trait results in negligible current through the elements when you apply normal voltage. This leads to a much simpler arrester design.An insulated housing surrounds series disks of zinc oxide in an MOV arrester. The disks have a conducting layer (generally aluminum) applied to their flat faces to ensure a proper contact and uniform current distribution within the disk. This design results in no "gaps;" thus, the reference to the MOV arrester as the "gapless" arrester. The MOV arrester design has become the most preferred because of its simplicity and resulting reduced purchase cost.

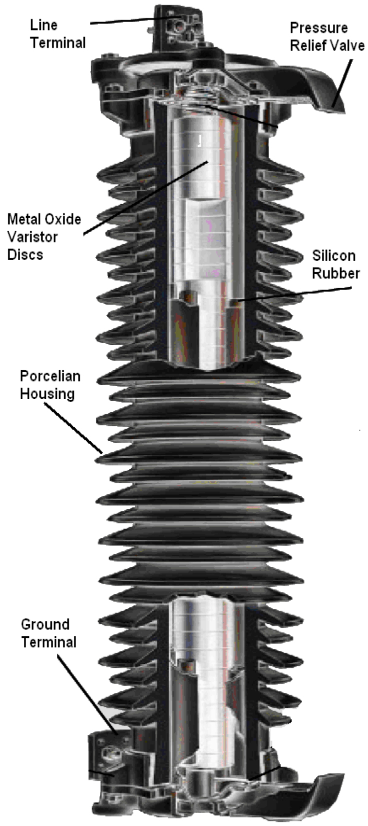


Fig.5.2. A Metal Oxide L.A

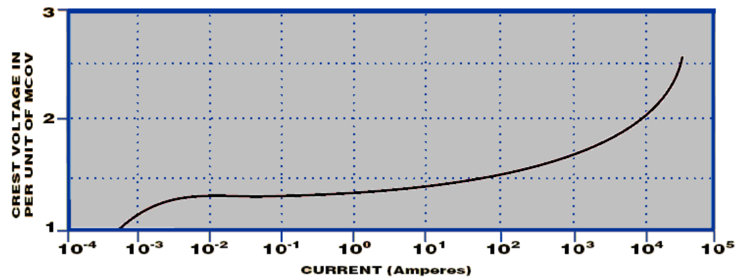


Fig.5.3 Operating Curve of a L.A

Transformers. Arresters will be located and connected as close as practicable to the transformer to be protected, in accordance with IEEE Std C62.2. In regions of high lightning incidence, surge arresters will be mounted on each of the incoming aerial line structures and directly on each of the main supply transformers. For a 132 KV and above system the ground terminal of the LA is to be solidly earthed through a Mild steel Iron Flat of min 100 mm width and 16 mm thickness connected to an earth pit filled with coke and rock salt provided with a water tap for watering the pit daily.

Metal-oxide type. A metal-oxide surge-arrester (MOSA) utilizing zinc-oxide blocks provides the best performance, as surge voltage conduction starts and stops promptly at a precise voltage level, thereby improving system protection. Failure is reduced, as there is no air gap contamination possibility; but there is always a small value of leakage current present at power frequencies. Therefore, the arrester's maximum power-frequency continuous operating voltage (MCOV) can not be exceeded.

5.6 Transformer Neutral Grounding

The need for neutral earthing

Limit the potential of current-carrying conductors with respect to the general mass of earth Provide a current return path for earth faults in order to allow protective devices to operate Neutral earthing is usually applied on the secondary winding of transformers it is different from equipment earthing which connects the metallic parts and enclosures to the earth to minimize electric shock.

Types of neutral earthing

Electrical systems are usually earthed via their star point or neutral.
There are three choices:
1) solidly earthed 2) earthed via impedance, usually a resistor 3) Isolated

Solidly earthed systems is used where high levels of fault current are observed and rotating machines are not connected in the system. High value earth faults can be cleared quickly. Solidly earthed systems provide the best control of transient and temporary overvoltages that can arise between earth and the electrical system. Insulation that is applied between phase and earth can be rated based on the phase to earth voltage. Lower rated insulation can reduce the cost of electrical systems and equipment. This is used in all 110 KV and above systems and for distribution transformer upto 11 KV and where the impedance on the primary side(the transmission lines) limits the fault current through the transformer when there is a fault on the secondary side.

Isolated : having no neutral earth the voltage rises in the transformer windings as it offers high impedance to fault currents and causes insulation breakdown systems have one advantage. They can continue operating in the presence of a single earth fault. This is because there is no return path available for the flow of earth fault current. Hence protective devices will not operate. Insulation that is applied between phase and earth must be rated based on the phase to phase voltage, and often for even higher voltages. This system is not adopted due to it's disadvantages.

Neutral earthing via an impedance is employed when it is desirable to limit the magnitude of fault current to manageable levels. High levels of fault current are undesirable as they can lead to irreversible damage equipment and systems.the selection of the neutral resistor is vital for this system as it affects the operation of earth fault protection , to overcome this current transformers are provided in series with the neutral resistor which detects the flow of fault current and activates the protection system. The reliability of power supply is improved as the system, Neutral resistors are used in MV transformers (11 to 33 KV)

Neutral earthing resistors :
A neutral Earthing resistor restricts the flow of current during an earth fault on an AC distribution system. It is connected between the neural point of a transformer and earth. Although a neutral earthing resistor will probably be active for just a few seconds during its operational life, it musc offer dependable protection at all time in case of fault. Used in power distribution, mining and industrial installations, indoors and outdoors where equipment needs to be protected against arc voltages and currents.
Capacity : A neutral earthing resistor has a resistance value specified to limit the fault cyrrent within a system to a pre-determined value which is sufficiently low to prevent damage yet high enough to operate fault-clearing relays.
Each system is designed according to current and timeratings, which are specified to be compatible with the protection switch gear.
neutral earthing resistors are made from tough steel grids of a high quality iron-chrome-aluminium They are non-corroding and offer good electicity stability

Neutral Voltage displacement

Unbalance in loads on three phases cause shifting of neutral from earth potential. Neutral displacement is applicable for transformers with 'Star Point' solidly grounded. Under "solidly" grounded conditions, the potential of neutral should be equal to earth i.e. zero. But in such conditions when the earthing of the star point is imperfect the star to ground offers small resistance. This results in flow of negative sequence currents (because IR + IY + IB M 0) through neutral to ground, thereby causing shift of neutral from its earth potential, which is the neutral voltage displacement.

Unbalance voltages and displacement of neutral will result in decreased efficiency, negative torque, leakage currents, vibrations and overheating. Severe unbalance and neutral displacement could lead to malfunctioning of some equipment. Some types of loads like Xray machines; electric traction; induction and arc furnace may induce unbalance in the supply voltages and shift the voltage of neutral from earth potential.

The Distribution Licensee shall ensure that the neutral point voltage of the all 33/11 kV and 11/0.4 kV transformers with respect to earth will not have potential greater than 2% and 5% respectively of the no load phase-phase voltage of the transformer.

Chapter-6

6 TRANSFORMER TANK AND COOLING SYSTEM

6.1 Transformer Tank Requirements

The tank is manufactured by forming and welding steel plate to be used as a container for holding the core and coil assembly together with insulating oil. transformer tanks are designed to seal the transformer from the outside atmosphere and able to withstand the electromechanical forces, oil expansion and vibrations produced on load and fault conditions

Shall satisfy the following criteria

Strength to prevent tank rupture under low energy fault conditions:

- The transformer tank, cooling equipment and compartments subject to pressures shall be designed to withstand, without permanent deformation, pressures of at least twenty-five percent greater than maximum operating pressures. The maximum design withstand pressure shall be indicated on the nameplate.
- Include sufficient expansion volume to allow operation under specified load conditions.

The main cover shall be of welded onto the tank.
One or more hand-holes shall be provided in the tank cover for access to bushing connections and current transformers, when required. The opening shall be of sufficient size to allow removal of any CT.

- The transformer base shall be suitable for rolling or skidding in the direction of either tank base centerline.

The base shall be designed so the center of gravity of the transformer as assembled for transport does not fall outside the base for a tilt of fifteen degrees.

- Lifting lugs shall be provided at each corner of the tank. The lifting lugs shall be designed to provide a minimum safety factor of 5.
- Jacking area, pads or bosses shall be provided.
- Pulling provisions, for towing the transformer parallel to either centerline, shall be provided.
- Gaskets

The gaskets shall be compatible for the insulating fluid in the transformer tank.
Gaskets in continuous contact with Silicone fluid shall be Viton material.
Metal surfaces to which gaskets are applied shall be smooth, and shall have sufficient rigidity to assure proper compression of the gaskets.

Types of Tanks :
1. Plain steel sheet tank without external cooling for smaller ratings
2. Thick sheet boiler type plates with cooling tubes
3. Tanks with external radiators attached to the tank
4. Tanks with separated radiators connected by pipes

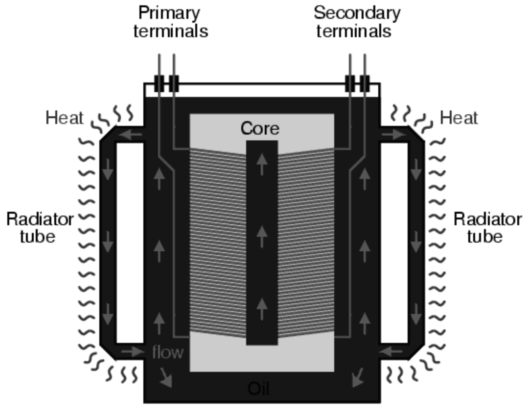


Fig.6.1. showing transformer core and radiator tubes

6.2 Tank Construction

Plain Sheet Steel tanks

Made of thin steel sheets of about 3 mm thickness the tank's surface is plain without any cooling tubes ,these tanks are used for housing small transformers upto 50 KVA rating.
Thicker sheets are used for the base depending upon the installation. the four side walls are made of a single steel sheet and welded vertically, electric welding is preffered

Thick boiler plate tanks:
This type of construction is used for self cooled distribution transformers of all sizes above 50 KVA cooling tubes are welded to the tank walls to obtain additional cooling surface and natural circulation of hot oil. High quality boiler plate steel of thickness from 5 mm to 12 mm is cut shaped and welded to get rigid construction stiffners are welded to the sides at an interval of above 1 mm to prevent bulging.
The tank is proof tested for pressure (7 psig) and vacuum (0.1 torr or below) as per the standards.
Cooling tubes are arranged at a spacing of about 8 cm centre to centre the bottom of the plate is thicker than the sides and is about 8 to 15 mm. The optimum dimensions of the tank and stiffeners are determined by using computer aided design tools. The interior corners of the transformer corners are welded to get added strength and to prevent leakage paths.

The transformer tanks are tested for leakage by filling them with oil and keeping them under pressure of 0.5 kg/cm² for several hours and all joints are applied with light blue chalk powder which turns dark in presence of oil undertaking location of minute leaks.
Surface treatment : the tanks are shot-blasted from inside and outside to prepare a good clean surface. The rough spots on welded joints are chipped and ground and cleaned thoroughly by blasting compressed air. A red oxide premier coat is applied and final paint as per specification is coated.
Other fitting and provisions :
The top cover of the transformer has to be provided with the following items
1) HV and LV terminal bushings
2) Neutral bushing if existing
3) Lifting bolts for top plate
4) Flange for connecting transformer with conservator
5) Flange for mounting tap changer head
6) Pocket for thermometer

7) oil drain pipe

The transformer of larger size has the following additional accessories
1) oil testing outlet with seal
2) oil and winding temperature indicators

Tanks with radiator banks :
For transformers of rating 5 MVA and above, the cooling tubes are insufficient to cool the transformer oil efficiently, separate detachable radiator (elliptical steel tubes welded inside pressed steel plates) connected on both sides of the transformer having an inlet and outlet valve a number of such radiators are connected to the transformer tank either on one side for transformers of less than 5MVA and on both sides above
5 MVA The radiators are connected to the transformer tank by means of shut-valves. This method allows individual radiators to be removed without draining oil from the transformer. The shut-off valve is provided with a position indicating handle and with a locking spring. The lower part of the radiators has a plug for oil outlet and the upper part a plug for air release.
Circulation of transformer oil takes place in the following manner. when the transformer is loaded the Hot oil inside the transformer rises to the top of the tank and gets into the radiator tubes (Inlet) and after circulating in the tubes and getting cooled the oil flows back into the tank through the bottom of the radiators (Outlet). For large transformers 30-100 MVA fans are provided on the sides or bottom of the radiator banks for better cooling of the oil.

Tanks with radiators are placed separately :
For very large and high voltage transformers the natural circulation of oil in radiators is not sufficient to cool the oil radiator banks are placed separately away from the tank and the oil is forced in circulation using pumps fans are provided for air circulation over the radiators, for better cooling water is also circulated over the radiator tubes, but care is to be taken for leakages.

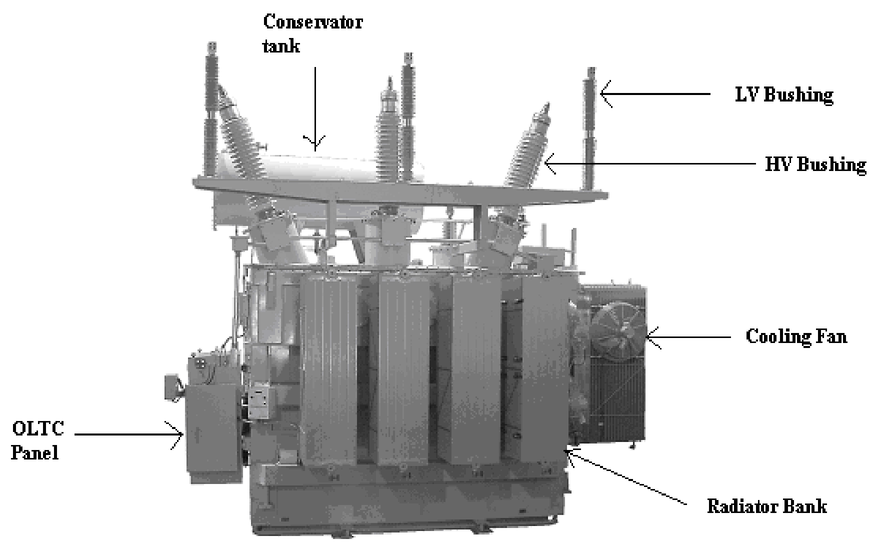


Fig.6.2 Picture of a transformer along with radiators and cooling fan

Accessories with the Transformer Tank :

The following components are fitted to the transformer tank according to the requirements
1) oil conservator
2) Breather
3) Oil sampler
4) Buchholz relay
5) Pressure relief valve
6) Oil level Indicator
7) Oil Temperatute Indicator
8) Winding temperature indicator
9) HV and LV bushings
10) Neutral Bushing
11) Tap changer
12) Cooling system (radiator or pipes)
13) Marshalling kiosk, etc.,

Cooling System :
Cooling of dry type transformers.

AN – Air Natural

AF – Air forced (by Fans)

Cooling for oil Immersed transformers

ONAN **-** Oil Natural Air Natural

ONAF **-** Oil Natural Air Forced

OFAF **-** Oil Forced Air Forced

ONWF **-** Oil Natural Water Forced

OFWF **-** Oil Forced Water Forced

Air Natural : Applicable for dry type transformers only (i.e Cast Resin and Resin Impregnated)
Air Forced : Also for dry type transformers air is forced on tank surface by a fan which is controlled by a thermostat in the tank
Oil Natural Air Natural : This is the most widely used method of cooling for oil filled transformers upto 30 MVA. In oil Natural cooling, the transformer is under load and the surrounding oil heated up due to circulating currents in core and winding, the oil is circulated in the tank by natural convection. Plain tanks without cooling tubes are used upto 50 KVA ratings above this rating cooling tubes are fitted to the tank for better circulation and cooling upto 5 MVA.
Oil Natural Air Forced :A number of Large Fans are mounted near the transformer radiators and either at the bottom (Large transformers 100 MVA) or on sides (30-75 MVA) depending on the design and , these fans are automatically switched on when the temperature of the transformer oil raises above a set value and off when it cools down below the set value.
Oil Forced Air Forced : For transformers above 100 MVA the ONAF system of cooling is not sufficient, hence oil is also forced into circulation for better cooling in addition to forced air circulation. A pump is used to force oil from the top of the transformer (outlet) into the radiator banks which are placed some distance from the tank and connected by inlet and outlet pipes.

Oil Natural Water Forced : This type of cooling is used in places where there is space restriction for and water is available freely, by using a pump water is circulated around the radiator tubes for cooling of the transformer oil which is circulating by natural convection. But nowadays this type of system is discontinued as present day transformer have better designed radiators and cooling systems.

6.3 Transformer Cooling

No-load losses and load losses are the two significant sources of heating considered in thermal modeling of power transformers. No-load losses are made up of hysteresis and eddy loss in the transformer core, and these losses are present whenever the transformer is energized. Hysteresis loss is due to the elementary magnets in the material aligning with the alternating magnetic field.
Eddy currents are induced in the core by the alternating magnetic field. The amount of hysteresis and eddy loss is dependent on the exciting voltage of the transformer.

Load losses are the more significant source of transformer heating, consisting of copper loss due to the winding resistance and stray load loss due to eddy currents in other structural parts of the transformer. The copper loss consists of both DC resistance loss, and winding eddy current loss. The amount of loss is dependent on transformer load current, as well as oil temperature. DC resistance loss increases with increasing temperature, while other load losses decrease with increasing oil temperature. All of these factors are considered in calculations of thermal transformer performance.

The basic method for cooling transformers is transferring heat from the core and windings to the insulating oil. Natural circulation of the oil transfers the heat to external radiators. The radiators increase the cooling surface area of the transformer tank. Pumps may be used to increase the flow of oil, increasing the efficiency of the radiators. In non-directed flow transformers, the pumped oil flows freely through the tank. In directed flow transformers, the pumped oil is forced to flow through the windings. Forced air cooling is commonly applied on large power transformers, using fans to blow air over the surface of the radiators, which can double the efficiency of the radiators. For some large power transformers, water cooling may replace large radiators. Large power transformers may also have additional ratings for multiple stages of forced cooling. Normally, only two stages are applied, providing transformer ratings equivalent to 133% and 167% of the self-cooled rating.
Both the IEEE and the IEC established standard designations for the various cooling modes of transformers. The IEEE has adopted the IEC designations. The designation completely describes the cooling method for the transformer, and the cooling method impacts the response of the transformer insulating oil to overload conditions. Table 6.1 lists the common transformer cooling designations.

Table 6.1: Transformer cooling designations

Old IEEE Cooling Designations		**IEC Equivalent**
Self-cooled	OA	ONAN
Forced air cooled	FA	ONAF
Directed-flow forced liquid cooled	FOA	ODAF
Water cooled	OW	OFWF
Forced liquid and water cooled	FOW	OFWF

Impact of Oil Temperature on Power Transformers INCREASING transformer load increases the temperature of the insulating oil, so loading above the nameplate rating involves some risk.

Transformers are rated at a maximum oil temperature rise over ambient, with modern transformers rated at 65º C rise above ambient. These risks include reduced dielectric integrity due to gassing, reduced mechanical strength and permanent deformation of structural components such as the core and windings, or possible damage to auxiliary equipment such as tap changers, bushings, or current transformers. Oil temperature, therefore, makes a good choice to use as the basis of a protection function, providing sensitivity to a number of possible transformer issues. Standard temperature limits are defined in the *IEEE Guide for Loading Mineral-Oil Immersed Power Transformers*, (described in the rest of this paper as the *Guide for Loading*) are listed in Table 6.2.

Table 6.2: Standard temperature limits, 65º C rise transformer, 30º ambient temperature

Standard temperature limits		
Average winding temperature rise	65º C	Above ambient
Hot-spot temperature rise	80º C	Above ambient
Top liquid temperature rise	65º C	Above ambient
Maximum temperature limit	110º C	Absolute

One factor in transformer over-temperature conditions is the loss of insulation life. Aging of the refined paper insulation is based on temperature, moisture content, and oxygen content over time. Modern oil preservation systems minimize the impact of moisture and oxygen on insulation life. Therefore, aging studies of transformers use the hottest-spot oil temperature to determine transformer life. [3]
The term "transformer life" is assumed to mean the insulation life of the transformer, not the total operational life. "Loss-of-life" is assumed to mean loss of the total insulation life of the transformer. For 65º C rise transformer operate at the maximum temperature, the *Guide for Loading* uses 65,000 hours (7.4 years) as normal life expectancy, based on 50% retained mechanical strength of the insulation. The *Guide for Loading* also states that 180,000 hours (20.6 years) is also a reasonable value for a normal life expectancy. This means, practically, that the transformer can be operated at full load for 65,000 hours over the total operational life of the transformer before the mechanical strength of the insulation is reduced by half, increasing the likelihood of failure during short circuits. The relationship between oil temperature and transformer life expectancy is given by the accelerating aging factor, FAA. FAA for 65º C rise transformers is defined as:

$$F_{AA} = e^{\left[\frac{15,000}{383} - \frac{15,000}{\Theta_H + 273}\right]} \text{ per unit,}$$

Where Θ*H* is the hottest-spot temperature (ºC)
The FAA is a multiplier for the rate of transformer aging, and is greater than 1 when the hottest-spot temperature exceeds the 30º C ambient design temperature limit of 110º C. This factor adjusts the normal life expectancy of the transformer for over-temperatures. For a transformer operated continuously at a specific temperature, the actual life expectancy is the normal life expectancy divided by the accelerating aging factor FAA.

For example, if $\Theta_H = 140^\circ$ C, then

$$F_{AA} = e^{\left[\frac{15,000}{383} - \frac{15,000}{\Theta_H + 273}\right]} = e^{\left[\frac{15,000}{383} - \frac{15,000}{140+273}\right]} = 17.2$$

$$Life\ expectancy = \frac{65,000}{17.2} = 3779\ hours$$

Chapter 7

7 TRANSFORMER WINDINGS

7.1 Winding Construction

Coils are wound on a laminated silicon steel core which provides a path for the magnetic flux. The coils comprise a number of turns of conductor, either copper or aluminum, wound as two electrically separate windings, called the primary winding and the secondary winding. The primary winding is connected to the source of voltage while the secondary winding is connected to the load. The ratio of primary to secondary turns is the same as the required ratio of primary to secondary voltages. Windings must be designed to ensure short circuit withstand capability, uniform surge voltage distribution and effective heat dissipation which are critical to transformer reliability.

Fig.7.1 Active Part of a 145 kV, 110 MVA generator transformer with off-circuit tap changers for alternative rated HV voltages and on-load tap changer for voltage regulation,Courtesy Ganz Transelektro Bulgaria

The high voltage and low voltage windings are constructed using (copper, aluminum) conductors. The conductors shall be insulated with a 220°C insulation. Transformer windings, insulation class 1.2 kV (600v) and below, shall be wound using foil or sheet conductors. A sheet wound coil allows free current distribution within the axial width of the conductor/coil to essentially eliminate axail forces under short circuit.

windings, insulation class 2.5 kV (2400v) and above, shall be wound using wire conductors. The high voltage winding shall be wound over the low voltage winding with sufficient mechanical bracing to prevent movement during fault conditions and sufficient solid Class 220°C insulation to isolate the high voltage winding dielectric potential from the low voltage windings.

Layer winding

For low voltage, i.e. less than 10 KV class windings, the winding technique used almost exclusively is the layer winding technique, also sometimes called **helical** winding or barrel winding. In this technique, the turns required for the winding are wound in one or more concentric layers connected in series, with the turns of each layer being wound side by side along the axial length of the coil until the layer is full.

The conductors of the winding are insulated and so between turns there will be a minimum of two thicknesses of insulation. Between each pair of layers there will be layers of insulation material and/or an air duct.

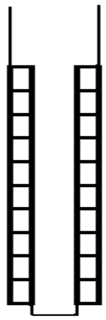


Fig.7.2 Layer or helical winding

Low voltage windings will generally be wound top to bottom, bottom to top etc. using a continuous conductor, until all layers are complete. High voltage windings, i.e. above 600 Volt class, may be wound in the same way, provided the voltage between layers is not too great. To reduce the voltage stress between layers, high voltage windings are often wound in only one direction, for example, top to bottom. When the first layer of winding is complete, the winding conductor is laid across the completed layer from bottom to top and then the next layer is wound, again from top to bottom. In this way, the voltage stress between layers is halved. The conductor must, of course, have additional insulation where it crosses the winding from bottom to top.

Disc winding

In the disc winding, the required number of turns are wound in a number of horizontal discs paced along the axial length of the coil. The conductor is usually rectangular in cross-section and the turns are wound in a radial direction, one on top of the other i.e. one turn per layer, until the required number of turns per disc has been wound. The conductor is then moved to the next disc and the process repeated until all turns have been wound. There is an air space, or duct, between each pair of discs. The disc winding requires insulation only on the conductor itself, no additional insulation is required between layers, as in the layer winding.

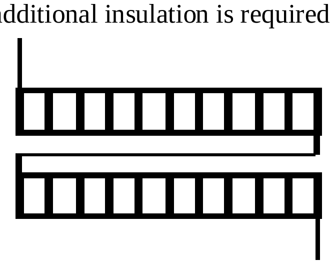


Fig.7.3 Disc winding

The disc wound high voltage winding is usually wound in two halves, in order that the required voltage adjustment taps may be positioned at the electrical center of the winding. In this way the magnetic, or effective length of the winding is maintained, irrespective of which tap is used, and therefore the magnetic balance between primary and secondary windings is always close to its optimum. This is essential to maintain the short circuit strength of the winding, and reduces the axial electromagnetic forces which arise when the windings are not perfectly balanced.

Characteristics of Layer wound coils
A layer wound coil requires insulation between layers, in addition to the conductor insulation. The thickness of insulation required will depend upon the voltage stress between layers, and comprises one or more thicknesses of the appropriate insulation material. In practice, due to the nature of the construction of a layer wound coil, the finished coil will have several unavoidable small air pockets between turns and between layers. Many of these air pockets will become filled with resin during vacuum pressure impregnation of the coil. However, it sometimes happens that some air pockets remain and it is in these air pockets that partial discharges can occur, greatly increasing the possibility of premature aging of the insulation and eventual failure. Catastrophic failure can occur within a few months of energization.
Under short circuit conditions, the electromagnetic forces developed cause transformer windings to attempt to telescope. At the same time the coil end blocking is trying to prevent movement. The result is often that the turns of the winding have a tendency to slip over one another, causing turn-to turn failure, due to abrasion of the insulation as the turns rub together.

Characteristics of Disc wound coils
The major advantage of the disc wound coil lies in its open construction and relative lack of insulation. For a 15kV class transformer employing a disc wound primary winding, the number of discs will typically be in the range 36 to 48, resulting in a relatively low voltage per disc. Since each disc is separated from the next by an air space, the voltage stress between discs can easily be handled by the combination of conductor insulation and air, no additional insulation being necessary. Each disc comprises a number of turns with each turn occupying one layer, i.e. one turn per layer: the voltage stress between layers is therefore the same as the voltage stress between turns and again, can easily be handled by the conductor insulation. The turns of each disc, being wound tightly together provide almost no possibility of air pockets being present within the disc.
Unlike the layer wound coil, the disc wound coil provides good impulse voltage distribution, due to its inherently low value of ground capacitance and high series capacitance. The disc wound coil also displays excellent short circuit strength. Each disc by itself is mechanically very strong and the complete assembly of discs are held very securely in place. While the electromagnetic forces resulting from a short circuit result in a tendency, for the windings to telescope, the high voltage turns usually remain intact relative to each other. Instead, the complete disc has a tendency to distort as an assembly, with all the turns distorting by the same amount. The transformer can often continue to function, despite the distortion, until a convenient time arises for repair.

7.2 Insulation and drying system

The turns of conductor forming the primary and secondary windings must be insulated from one another, while the primary winding must be insulated from the secondary winding and both the primary and secondary windings must be insulated from ground. The insulation of turns and windings is collectively called the insulation system of the transformer.
The insulation system must be designed to withstand the effects of lightning strikes and switching surges to which the transformer is subjected, in addition to the normal operating voltages. A further requirement of the insulation system is that it must withstand the environmental conditions to which it is exposed, such as moisture, dust etc. A variety of techniques and materials are employed to achieve the necessary performance characteristics of the insulation system.

For dry transformers epoxy resin reinforced with glass fibre is used as an insulation for the windings. The internal insulation system is based on pure mineral oil, and cellulose in the form of paper, pressboard, and sometimes selected natural wood.
An oil barrier system is used as the main insulation medium and moulded angle rings for end insulation. Major oil gaps between the windings and earthed parts are divided into thin oil layers by means of press board barrier cylinders enabling uniform drying and PD (Partial Discharge) free insulation even at high electric stresses. Pre-compressed press board spacers and moulded end-barriers used in the active part provide a rigid insulation structure with low PD levels.
Moisture content in insulating materials of winding assembly is removed by application of heat and vacuum in a separate drying oven (Winding Autoclave) before windings are individually pressed in a hydraulic press. As the active part can absorb moisture during the assembly process a final drying process is carried out in a completely automated vapour phase drying (VPD) plant. This ensures thorough and uniform drying resulting in a clean and dry core coil assembly (active part) which ensures long transformer life.
Cellulose insulation is used in most power transformers. Paper-oil insulation is also used combination of oil and fibrous cellulose materials has dominated the technology of power transformer insulation since electrification began

Cellulose material

The cellulose material parts in modern transformers are thin paper tape for paper lap covering of the conductor, solid pressboard in the form of strips, spacers, large cylinders and moulded collars, and some structural massive pressboard supports for windings and connecting cables inside the tank.
The raw material for both paper and pressboard is pine from subarctic forests. The paper and board materials are made by the sulphate process and are unbleached.
Textile wrapping and impregnation varnishes for mechanical stabilization of coils are for the same reason not used today. Selected natural wood is used for less critical mechanical support structures, e g paper-covered connecting cables.

Pressboard

Precompressed boards are made as large sheets. They are compressed and dried under heat in a hydraulic press from a soaking wet condition to full dryness. The maximum dry thickness is about 8 mm. It is a mechanically tough material that can be machined with sharp wood-working tools. Heavy blocks for structural parts are machined from blocks that are glued together from several sheets of precompressed material.
A softer pressboard variant is used to mould parts with complex geometries. The material is soaked, and will then be dried under compression on moulding madrels or between metal tools to form angle collars or snouts of various specified shapes.

Vacuum Pressure Encapsulation Process

The completed core and coil assembly is to be dried at atmospheric pressure in an oven through which hot air is continuously circulated. The assembly is then to be vacuum pressure encapsulated via a multi-cycle process. This process requires that coils receive a minimum of four (4) cycles and the core and clamping structure receive a minimum of two (2) cycles in silicone varnish. The varnish shall be applied in consistent coatings to give a uniform shield of silicone varnish. The VPE process shall effectively encapsulate the entire core and coil assembly that results in a unit which is virtually impermeable to moisture, dust, dirt, salt air and other industrial contaminants.

Transformer oil

Transformer oil is usually a highly-refined mineral oil that is stable at high temperatures and has excellent electrical insulating properties. It is used in oil-filled transformers, some types of high voltage capacitors, fluorescent lamp ballasts, and some types of high voltage switches and circuit breakers. It's functions are to insulate, suppress corona and arcing, and to serve as a coolant.

The oil cools the transformer, and provides part of the electrical insulation between internal live parts. It has to be stable at high temperatures so that a small short or arc will not cause a breakdown or fire. To improve cooling of large power transformers, the oil-filled tank may have radiators through which the oil circulates by natural convection.

Prior to about 1970, polychlorinated biphenyl (PCB) was often used as a dielectric fluid since it was not flammable. However, under incomplete combustion, PCBs can form highly toxic products, Furans, etc. Due to the stability of PCB and its environmental accumulation, it has not being used in new equipment since late 1960's . Today, nontoxic, stable silicone-based or fluorinated hydrocarbons may be used, where the added expense of a fire-resistant liquid offsets additional building cost for a transformer vault. Other less-flammable fluids such as canola oil may be used, but all fire resistant fluids have various drawbacks in performance, cost, or toxicity compared with mineral oil.

7.3 Transformer Impedance

Impedance of the transformers has a material effect on system stability, short-circuit currents, and transmission line regulation, and it is usually desirable to keep the impedance at the lower limit of normal impedance design values. Table 7.1 illustrates the range of values available in a normal two-winding transformer design (values shown are for GSU transformers with 13.8-kV low voltage).

Table 7.1

Nominal System KV	Winding BIL KV	Typical Impedance values		Impedance at Equiv. 55 ˚C KVA	
		Minimum	Maximum	Minimum	Maximum
15	110	5.0	7.5	8.34	12.5
25	150	5.0	7.5	8.34	12.5
34.5	200	5.25	8.0	8.75	14.33
46	250	5.60	8.4	9.34	14.0
69	350	6.1	9.15	10.17	15.25
115	450	5.9	8.85	9.84	14.75
138	550	6.4	9.6	10.67	16.0
161	650	6.9	10.35	11.50	17.25
230	825	7.5	11.25	12.5	18 .75
500	1425	10.95	15.6	18.25	26.0

Impedances within the limits shown are furnished at no increase in transformer cost.
Transformers can be furnished with lower or higher values of impedance at an increase in cost. The approximate effect of higher- or lower-than-normal impedances on the cost of transformers is given in Table 7.2.
The value of transformer impedance should be determined giving consideration to impacts on selection of the interrupting capacities of station breakers and on the ability of the generators to aid in regulating transmission line voltage.

Table 7.2

STANDARD IMPEDANCE X	INCREASE IN TRANSFORMER COST
1.45-1.41	3%
1.40-1.36	2%
1.35-1.31	1%
0.90-0.86	2%
0.85-0.81	4%
0.80-0.76	6%

Transformer impedances should be selected based on system and plant fault study results.
Impedances shown are subject to a tolerance of plus or minus
In making comparisons or specifying the value of impedance of transformers, care should be taken to place all transformers on a common basis. Impedance of a transformer is a direct function of its rating, and when a transformer has more than one different rating, it has a different impedance for each rating. For example, to obtain the impedance of a forced-air-cooled transformer at the forced-air-cooled rating when the impedance at its self-cooled rating is given, it is necessary to multiply the impedance for the self-cooled rating by the ratio of the forced-air-cooled rating to the self-cooled rating.

7.4 Insulation system

The dielectric tests of the transformer before delivery are entirely directed to verify the internal insulation system. The external insulation of the bushings is covered by separate component tests.

Impulse tests
The tests normally include impulse testing on the terminals, where a steep-fronted impulse waveshape simulates a lightning stroke close to a transformer in service. For very high voltage transformers an additional impulse test is applied, using a wave shape with longer duration and lower amplitude, but larger energy content. The impulse tests are monitored with oscillographs or equivalent transient recorders. This analysis is quite intricate but gives reliable information on any possible disturbances in the transformer.

Separate source voltage test
The correct assembly of the transformer is verified through tests using AC overvoltage. The separate source voltage test is a test in which the whole of a winding is brought up to the same AC potential by connecting one of its terminals to a test transformer.(With certain windings having ”non-uniform insulation” and a neutral terminal intended for direct earthing this test is not applicable directly.)

Induced voltage test
For the induced voltage test the transformer is connected for normal operation, and the transformer is tested at an elevated power frequency to avoid overexcitation of the core. The test is run either with a high voltage during less than a minute, or with a more moderate voltage during a longer application time with simultaneous observation of any possible partial discharge phenomena in the transformer. This test method is a relatively recent quality control addition to enhance the assessment of the transformer’s insulation system.

IR testing. The IR of each winding should be measured using a megohmmeter in accordance with Sections 10.9 through 10.9.4 of the ANSI/IEEE C57.12.91-1979 Standard, Test Code for Dry-Type Distribution and Power Transformers. The transformer should be deenergized and electrically isolated with all terminals of each winding shorted together. The windings not being tested should be grounded. The megohmmeter should be applied between each winding and ground (high voltage to ground and low voltage to ground) and between each set of windings (high voltage to low voltage). The megohm values along with the description of the instrument, voltage level, humidity, and temperature should be recorded for future reference.

The minimum megohm value for a winding should be 200 times the rated voltage of the winding divided by 1000. For example, a winding rated at 13.2kV would have a minimum acceptable value of 2640 megohms ([13,200V x 200] / 1000). If previously recorded readings taken under similar conditions are more than 50% higher, you should have the transformer thoroughly inspected, with acceptance tests performed before reenergizing.

7.5 Megger details and Usage.

The megger is a portable instrument used to measure insulation resistance. The megger consists of a hand-driven DC generator and a direct reading ohm meter. A simplified circuit diagram of the instrument is shown in Figure 1.
The moving element of the ohm meter consists of two coils, A and B, which are rigidly mounted to a pivoted central shaft and are free to rotate over a C-shaped core (C on Figure 1). These coils are connected by means of flexible leads. The moving element may point in any meter position when the generator is not in operation.
As current provided by the hand-driven generator flows through Coil B, the coil will tend to set itself at right angles to the field of the permanent magnet. With the test terminals open, giving an infinite resistance, no current flows in Coil A. Thereby, Coil B will govern the motion of the rotating element, causing it to move to the extreme counter-clockwise position, which is marked as infinite resistance.

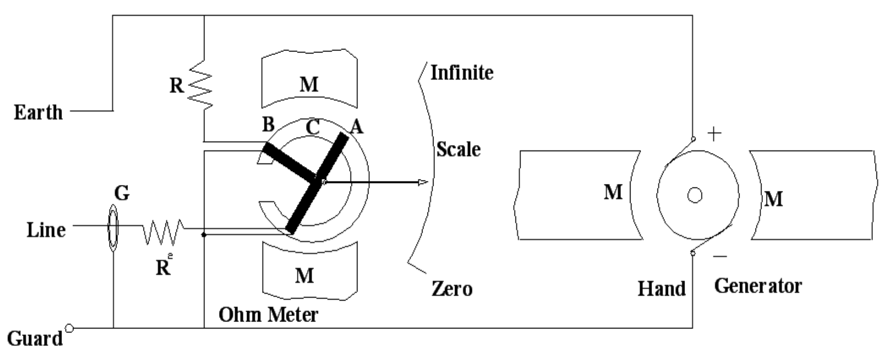


Figure.7.4 Megger details

Coil A is wound in a manner to produce a clockwise torque on the moving element. With the terminals marked "line" and "earth" shorted, giving a zero resistance, the current flow through the Coil A is sufficient to produce enough torque to overcome the torque of Coil B. The pointer then moves to the

extreme clockwise position, which is marked as zero resistance. Resistance (Rl) will protect Coil A from excessive current flow in this condition.
When an unknown resistance is connected across the test terminals, line and earth, the opposing torques of Coils A and B balance each other so that the instrument pointer comes to rest at some point on the scale. The scale is calibrated such that the pointer directly indicates the value of resistance being measured.

Insulation resistance measured with the transformer cold is greater than when measured with it hot and is also greater out of oil than when immersed in oil. Therefore, in order to determine the condition of the insulation, all of the measured values must be reduced to a fixed set of conditions. The reference conditions are a temperature of 20deg C and with the transformer filled with dry transformer oil in good condition. For these conditions the minimum
satisfactory insulation resistance corresponding to each normal line to line voltage class is given. Corrected measured values lower than those shown in Table 1 indicate that that transformer should be dried before energizing.
The measured insulation resistance at the transformer temperature is corrected to 20°C by multiplying the measured value by the correction factor corresponding to the transformer temperature (Figure 2). If the insulation resistance is measured with the transformer out of oil the measured values should first be divided by 20 and then corrected for temperature. It is desirable to have the temperature of the transformer between +40°C and 0°C to keep from making large corrections

Table 7.3 Guide for Minimum Insulation resistance in oil at 30 deg C

Voltage class KV	MegaOhms		Voltage class KV	MegaOhms
1.2	35		92	2500
2.5	70		115	3150
5	135		135	3750
9	250		160	4350
15	400		196	5400
25	700		230	6300
35	950		287	7800
46	1250		345	9500
69	1900			

METHOD OF MEASUREMENT USING MEGGER
The best method to measure insulation resistance is by a megger. This instrument is very convenient to use and indicates the megohm resistance directly. To get uniform results, measurements of insulation resistance with the megger type of instrument should follow a regular procedure
The recommended practice in measuring insulation resistance is to always ground the tank and the core iron or be sure they are grounded. Short-circuit each winding of the transformer at the bushing terminals. Resistance measurements are then made between each winding and all other windings grounded.
Windings are never left floating for insulation resistance measurements. Solidly grounded winding must have the ground removed in order to measure the insulation resistance of the winding grounded. If the ground cannot be removed, as in the case of some windings with solidly grounded neutrals, the insulation resistance of the winding cannot be measured. Treat it as part of the grounded section of the circuit.
For example, in the case of a three-winding transformer, the high-voltage, tertiary-voltage, and low-voltage windings are each short-circuited by connecting their terminals together. The high-voltage

winding insulation resistance is measured by connecting the high voltage terminals to the line or resistance terminal of the megger.
The low-voltage and tertiary-voltage windings are connected together and to the ground terminal of the megger. The guard terminal of the megger, if the instrument has a guard terminal, is not used but left floating.

The resistance measured is commonly designated the H-LTG resistance. Likewise, the other windings are measured and the measurements called T-HLG and L-HTG resistances. Two-winding transformer would have only two resistances, H-LG and L-HG.
The instrument used to measure the resistance should have a voltage output of at least 500 volts. The maximum insulation resistance to be measured must be less than the megohym rating of the instrument. Resistance readings at the extreme upper end of the instrument scale are not reliable. Where this condition exists, an instrument capable of measuring a higher resistance should not be used. The measuring lead should be air insulated from all other leads and from the ground and grounded objects in order to prevent misleading results due to measuring conductor insulation resistance instead of the insulation resistance.
The megger type of instrument may be motor driven, hand-cranked or supplied by a rectifier instrument is used, the insulation resistance indicated by the instrument should be recorded approximately one minute after the voltage from the instrument is applied to the transformer. In other words, the voltage from the instrument should be applied for one minute before recording the resistance value.
With a hand-cranked instrument, the time interval after starting to crank the instrument until recording the resistance value indicated should both be less than 30 seconds and preferably should be one minute. This reduction in time is due to the difficulty of cranking a megger continuously for one minute.
In any case, the time interval during which the voltage is applied should be consistent throughout the tests and should be recorded with the insulation resistance values. All measurements should be made with the same procedure to avoid errors and to obtain comparative results.

7.6 Transformer Oil

The majority of power transformers in operation today are filled with mineral oil. The primary function of the oil is to provide a high dielectric insulating material and an efficient coolant. It is a by-product obtained by crude oil refining to fuels such as petrol or diesel mixed with additives to give a suitable chemical substance which is called a mineral insulating oil.

DESCRIPTION
Transformer Oil is a high quality electrical insulating oil. It is manufactured using specially selected base stocks to help provide protection against oxidation and sludge formation. Careful processing and handling ensure that the oil is stable and free of water and other contaminants and remains so until it reaches the user.
Transformer Oil is recommended for use as an electrical insulating oil in applications such as transformers, oil immersed switchgear, circuit breakers, oil filled capacitors, tap changers, electrical enclosures and fuses, where an oil meeting the Australian Standard, British Standards Institution, International Electro technical Commission or other comparable specification is required by the equipment manufacturer or user.
It should not be used where safety considerations require the use of non-flammable insulating oil

Dissolved Gas Analysis (DGA)

When the insulation of an oil-filled transformer deteriorates, it generates a number of gases from the decomposition of insulation. These gases dissolve in the transformer oil.

The DGA is a laboratory test to analyse the types and quantities of dissolved gases from oil samples taken from transformers.

The DGA tests are carried out by qualified chemists at accredited laboratory , according to ASTM D3612.

Nine types of dissolved gases in the mineral transformer oil sample are being analyzed as per the Standards' requirements.

7.7 Transformer Oil Quality Tests

The following Oil Quality Tests are performed to check is the conditions of transformer oils. These tests are carried out by qualified chemists at accredited laboratories.
Dielectric Breakdown Voltage Test (IEC 60156)
This test determines if the transformer oil has adequate insulating strength. Low insulating strength of oil can lead to transformer failure.
Water Content Test (IEC 60814)
This test determines the water content in the insulating oil based on the Karl Fisher method. The presence of water can adversely affect the dielectric strengths of the insulating oil.

Acidity Test (IEC 60296)
This test measures the acids content of the oil. The build-up of acidic compounds cause the formation of sludge in the transformer. Sludge has an adverse effect on the cooling ability of the insulating oil that can lead to transformer overheating.

Corrosive Sulphur Test (ISO 5662)
This test detects the presence of corrosive sulphur in the insulating oil. Sulphur can cause corrosion to the winding insulation and conductor of transformer.

From the quantity and type of each gas detected, engineers can determine if the transformer has partial discharge, thermal fault or arcing problem.

SIGNIFICANCE OF TESTS
The following comments and interpretations, based on both technical understanding as well as empirical knowledge, emphasize those properties which are functionally important to transformer oils:

Aniline Point : The aniline point is the temperature at which a mixture of aniline and oil separates. It provides a rough indication of the total aromatic content, and relates to the solvency of the oil for materials which are in contact with the oil. The lower the aniline point, the greater the solvency effect.

Carbon Type Composition : The carbon type composition characterizes an insulating oil in terms of the percentage of aromatic, naphthenic, and paraffinic carbons. It can be used to detect changes in oil composition and to relate certain phenomena that have been demonstrated to be related to oil composition.

Color : The color of a new oil is generally accepted as an index of the degree of refinement it is of pale yellow for new oil. For oils in service, an increasing or high color number is an indication of contamination, deterioration, or both.

Corrosive Sulfur : This test detects the presence of objectionable quantities of elemental and thermally unstable sulfur-bearing compounds in an oil. When present, these compounds can cause corrosion of certain transformer metals such as copper and silver.

Dielectric Breakdown : The dielectric breakdown is the minimum voltage at which electrical flashover occurs in an oil. It is a measure of the ability of an oil to withstand electrical stress at power frequencies without failure. A low value for the dielectric-breakdown voltage generally serves to indicate the presence of contaminants such as water, dirt, or other conducting particles in the oil.

Water Content : A low water content is necessary to obtain and maintain acceptable electrical strength and low dielectric losses in insulation systems.

Flash Point : The flash point is the minimum temperature at which heated oil gives off sufficient vapor to form a flammable mixture with air. It is an indicator of the volatility of the oil.

Furanic Compounds : Furanic compounds are generated as byproducts of the degradation of cellulosic materials such as insulating paper, pressboard, and wood. These compounds serve as indicators of insulation degradations. Because they are dissolved in the oil, furanic compounds can readily be sampled and tested by high performance liquid chromatography (HPLC). No significant quantity should be detected in new oils.

Impulse Breakdown Voltage : The impulse breakdown voltage is the voltage at which electrical flashover occurs in an oil under impulse conditions. It indicates the ability of an oil to resist transient voltage stresses such as those caused by nearby lightning strokes and high-voltage switching surges. The results are dependent on electrode geometry, spacing, and polarity.

Interfacial Tension : The interfacial tension of an oil is the force in dynes per centimeter required to rupture the oil film existing at an oil-water interface. When certain contaminants such as soaps, paints, varnishes, and oxidation products are present in the oil, the film strength of the oil is weakened, thus requiring less force to rupture. For oils in service, a decreasing value indicates the accumulation of contaminants, oxidation products, or both. It is a precursor of objectionable oxidation products which may attack the insulation and interfere with the cooling of transformer windings.

Neutralization Number : The neutralization number of an oil is a measure of the amount of acidic or alkaline materials present. As oils age in service, the acidity and therefore the neutralization number increases. A used oil having a high neutralization number indicates that the oil is either oxidized or contaminated with materials such as varnish, paint, or other foreign matter. (A basic neutralization number results from an alkaline contaminant in the oil.)

Pour Point : The pour point is the lowest temperature at which oil will just flow. A low pour point is important, particularly in cold climates, to ensure that the oil will circulate and serve its purpose as an insulating and cooling medium. It may be useful for identifying the type (naphthenic, paraffinic) of oils.

Power Factor : The power factor of an insulating oil is the cosine of the phase angle between a sinusoidal potential applied to the oil and the resulting current. Power factor indicates the dielectric loss of an oil; thus the dielectric heating. A high power factor is an indication of the presence of contamination or deterioration products such as moisture, carbon or other conducting matter, metal soaps and products of oxidation.

Specific Gravity : The specific gravity of an oil is the ratio of the weights of equal volumes of oil and water determined under specified conditions. In extremely cold climates, specific gravity has been used to determine whether ice, resulting from the freezing of water in oil-filled apparatus, will float on the oil and possibly result in flashover of conductors extending above the oil level. The specific gravity of mineral oil influences the heat transfer rates. Oils of different specific gravity may not readily mix when added to each other and precautions should be taken to ensure mixing.

Oxidation Inhibitor Content : These tests provide a method for the quantitative determination of the amount of oxidation inhibitor (2,6-ditertiary butyl-paracresol or 2,6 ditertiary phenol) present in an inhibited oil. Control of the inhibitor content is an important factor in maintaining long service life of inhibited insulating oils.

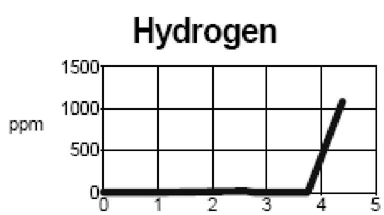
Oxidation Stability (acid/sludge) : The acid/sludge test is a method of assessing the oxidation resistance of an oil by determining the amount of acid/sludge products formed when tested under certain prescribed conditions. Oils which meet or exceed the requirements tend to preserve insulation system life and ensure acceptable heat transfer. The test may also be used to check the performance consistency of this characteristic of production oils.

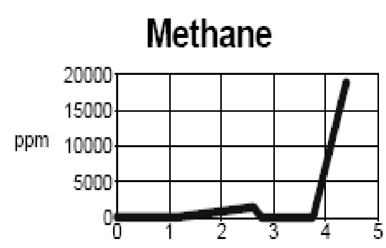
Gassing Under Electrical Stress : The gassing tendency is defined as the rate of gas evolved or absorbed by an insulating oil when subjected to electrical stress of sufficient intensity to cause ionization. The characteristic is positive if gas is evolved and negative if gas is absorbed.

Polychlorinated Biphenyls : Regulations prohibiting the commercial distribution of polychlorinated biphenyls (PCBs) mandate that insulating oils be examined for PCB contamination levels to assure that new products do not contain detectable amounts.

Viscosity : Viscosity is the resistance of oil to flow under specified conditions. The viscosity of oil used as a coolant influences heat transfer rates and consequently the temperature rise of an apparatus. The viscosity of an oil also influences the speed of moving parts in tap changers and circuit breakers. High viscosity oils are less desirable, especially in cold climates.

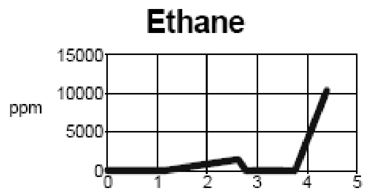
Fig.7.5 Showing the effect of different gases on transformer life

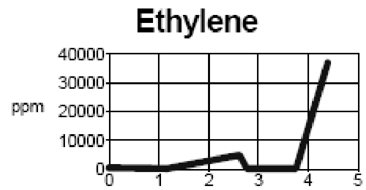




Years in Service

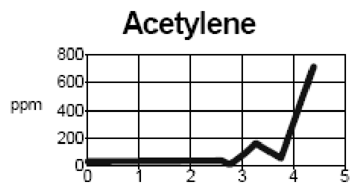
Years in Service

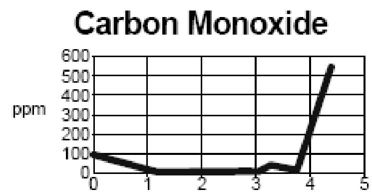




Years in Service

Years in Service





Years in Service

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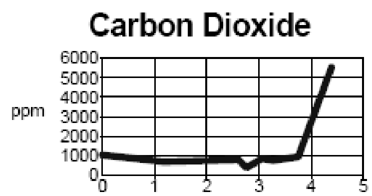
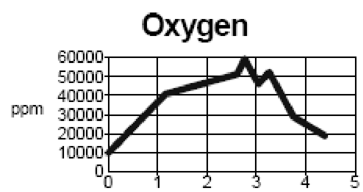
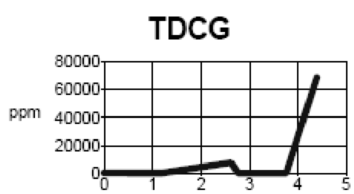




Years in Service

Years in Service



Years in Service

7.8 Gas analysis of transformer

Table 7.4

Type Of Gas	Caused By
CARBON MONOXIDE, CO CARBON DIOXIDE, CO_2	AGEING
HYDROGEN, H_2 ACETYLENE, C_2H_2	ELECTRIC ARCS
ETHANE, C_2H_6 ETHENE, C_2H_4 PROPANE, C_3H_6	LOCAL OVERHEATING
HYDROGEN, H_2	

METHANE,	CH_4	CORONA

Oxidation

The oxidation of transformer oil begins as soon as the transformer is energized. A chemical reaction occurs when the oil is exposed to a combination of heat, oxygen, and core and coil components. As the process of oxidation progresses, acids and polar compounds are formed and in turn become sludge. This sludge will then coat heat transfer surfaces on the core/coil and the tank/radiators, reducing the heat transfer capacity of the system. The operational temperatures are increased, thus accelerating the degradation of the oil.

Oil Which Is In The Initial Stages Of Oxidization, Forming Acids And Polar Compounds. Some sludge deposits will be found in a small percentage of oils in this initial stage of oxidization (Acidity levels <.20mg KOH/g oil).

Oil Which Has Advanced In The Oxidization Process To The Point Where Sludge Deposits Have Been Formed. This precipitating sludge coats all surfaces of the transformers tank and radiator walls, as well as the core and coil oil ways. In so doing, heat transfer is reduced causing the transformer to operate at higher than normal temperatures, which in turn speeds up the oxidation process (Acidity levels of .20mg KOH/g oil or greater).

Moisture

Through Absorption From The Atmosphere Above The Oil Level. Many transformer tanks are designed to seal the transformer from the outside atmosphere; however, top side leaks may develop that allow normal temperature changes to cause breathing . With each new inhalation comes more moisture to be potentially dissolved in the oil. Units designed as free breathing also can experience a build-up of dissolved moisture. In extreme cases, top cover leaks may be present which can allow rain to enter into the unit directly.

Condensation Inside Transformers. The moisture is introduced by exposure to the atmosphere above the oil level. Sudden temperature changes can condense the moisture allowing it to run down the tank walls into the oil. There it will dissolve slowly.

Oxidation Of Oil And Paper Insulation. Since oil and paper are organic compounds containing hydrogen, gradual oxidation will allow the formation of moisture. This can account for a major portion of the moisture in badly deteriorated oils.

oil is deteriorated beyond an acidity level of .05mg KOH/g oil then moisture becomes a problem

Units with primary voltages above 15Kv should have dielectric readings of 30Kv or above and moisture contents below 25ppm.

Dielectric reading of less than 25Kv, and moisture contents above 30ppm signal the need for hot oil treatment

Hot Oil Treatment

By heating the oil to a maximum of 95 °C. Processing begins when the oil reaches a minimum of 65 °C. The heaters have the capability of 38°C temperature rise at the rate of 600 to 1200 GPH. From the heaters the oil enters the filteration chambers,. The Filteration Earth removes sludge, acid and polar compounds from the oil. Next, the oil enters the vacuum degassing chamber. Vacuum is maintained at a minimum of 70 cm. This part of the process removes dissolved moisture, air, and dissolved gases from the oil enabling a unit to be processed even while energized.

Chapter 8

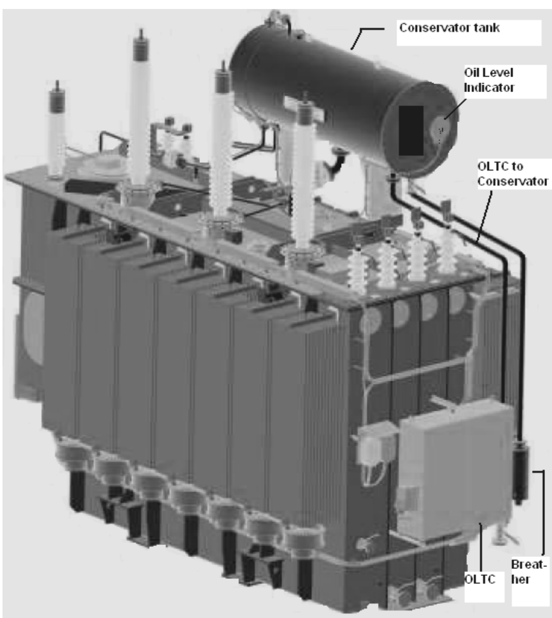
8 TRANSFORMER CONSERVATOR TANK

8.1 Function of the Conservator Tank

The conservator is an expansion vessel partly filled with oil and connected to the main transformer tank. Its function is to ensure that the transformer tank is completely filled with oil at all times

The Conservator, or Expansion-Tank System, seals the fluid from the atmosphere in the main tank by using an auxiliary tank partially filled with transformer fluid and connected to the main tank by piping. The system allows the transformer tank to remain full, despite expansion or contraction of the fluid due to temperature changes.

The oil conservator is mounted above the transformer tank and rests on a suitable rigid holding frame (or on a separate frame, in case of special request). Generally, the conservator has several separated sections. The largest section is for the thermal expansion of the transformer oil. In case of on load tap changers there is an other section for the thermal expansion of the oil in the hermetically sealed tap changer compartment. Third section or a separate small conservator is necessary if oil filled cable boxes are used. Each conservator section has adequate volume considering the connected total oil volume and the temperature variation in service. The oil of the different conservator sections cannot come into contact. The air space above the oil of each conservator section is connected through a pipeline to an air dryer which is mounted at a comfortable height for handling. The air dryer ensures the breathing of the air space above the oil level and controls the humidity. Syntetic or rubber bag conservators for airtight sealing of the oil are also available. The end-covers of the conservator are fixed by bolts. After removing them the inner part of the conservator can be cleaned. Each separated section of the conservator is provided with o magnetic type oil level indicator.



The oil level related to 20 C is marked. An oil filling pipe with a valve is connected to the conservator, a draining valve is located at the lowest point. Buchholz relays are placed in the connecting pipe between the conservator and the tank and between the conservator and the oil filled cable box, if it is used. Between the tap changer and the conservator an oil flow detecting protection relay is placed

Prior to assembling the conservator per manufacturer's instructions, the bladder should be checked carefully for any contamination or defects, such as a rip in the air bag. Also, proper operation of the oil level float should be verified.

The breather is provided with the conservator tank. The breather is typically a glass vessel whose top outlet is connected to the conservator ad bottom outlet is free to air. It is connected vertically with the constervator tank.

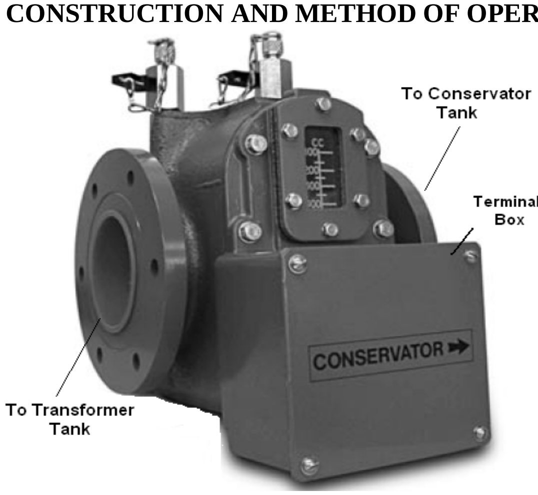
Fig.8.1 Conservator tank position
The breather has two chambers top chamber is filled with silicagel and bottom chamber which is of bowl type is filled with transformer oil. The air passes through the breathers. The moisture present in the air is absorbed by the silica gel. The dry air goes inside conservator tank when needed. The presence of moisture change colour of silica gel from blue to pink.
Conservators are so arranged that the lower part acts as a sump in which any impurities entering the conservator can collect. A valve/plug is fitted at the lowest point of the conservator for draining oil. The inside of the conservator should be cleaned every two or three years. The oil level indicators should be kept clean and Figure showing conservator and connections examined at regular intervals, and oil should be added when the level indicated is low.

8.2 Buchholz Relay connection

Most faults in an oil filled Transformer are accompanied by the generation of gas. By using a suitable relay the formation of this gas can be used as a warning of a developing fault. Double element relays can be used
for detecting minor or major faults. The alarm element will operate after a specified volume of gas has collected to give an alarm indication.
Examples of incipient faults are:
a. Broken-down core bolt insulation
b. Shorted laminations
c. Bad contacts
d. Overheating of part of the windings
The alarm element will also operate in the event of oil leakage or if air enters the cooling system.
The trip element will be operated by an oil surge in the event of more serious faults such as:
a. Earth faults
b. Winding short circuits
c. Puncture of bushings
d. Short circuits between phases
The trip element will also operate if a rapid loss of oil occurs.

MOUNTING POSITION
The relay should be mounted in the connecting pipe between the transformer and the conservator tank. This pipe should be as long and as straight as possible, and must be arranged to slope upwards, towards the
conservator, at an angle within the limits of 3 to 7 degrees to the horizontal.
There should be a straight run on the transformer side of the relay of at lease five times the internal diameter of the pipe, and at least three times this diameter on the conservator side.

CONSTRUCTION AND METHOD OF OPERATION



The relay consists of a lightweight container fitted with two pivoted elements. It is situated in the pipe line
between the transformer and the conservator tank, so that under normal conditions it is full of oil. The operating force relies upon the principle that when a body is immersed in a liquid it appears to lose weight.

Fig.8.2 Buchholz relay
Mercury Swithes
Mercury switches are employed of a special design to prevent mal-operation due to excessive transformer vibration. A sample relay of this type has to be submitted to a continuous vibratory type test. . The mercury switches test connected to sensitive detecting equipment and no mal-operations should be recorded. The mercury switches are to be spring mounted within the switch cylinders and protected from possible damage. Alarm and trip circuit mercury switches will make break and carry continuously
2 Amps at 250 Volts A.C or D.C. They will also make and carry for 0.5 sec. 10 Amps at 250 Volts A.C. or D.C.

PRINCIPAL OF OPERATION

The operating mechanism consists of a solid non-metallic cylinder containing the mercury switch, counterbalanced by a smaller solid metal cylinder. Both cylinders are jointed and free to rotate about the same axis, the amount of rotation being controlled by stops. When the relay is empty of oil, the
weight of the switch cylinder predominates and the switch system rests against the bottom stop, the mercury switch being in the closed circuit position. When the relay is full of oil, both cylinders appear to lose weight. Due to the different densities, the switch cylinder appears to lose enough weight to enable the weight of the counterbalance cylinder to predominate and rotate the whole system until it reaches the top stop, with the mercury switch in the open position.

"ALARM" OPERATION

When a slight or incipient fault occurs within the transformer, the gas generated will collect in the top of the relay housing. As gas collects, the oil level will fall and increasing amounts of the alarm switch will appear above the oil level. This results in gradual restoration of the apparent lost weight, until the weight of the switch cylinder predominates. The element rotates as the oil level continues to fall and eventually the alarm switch operates.

TRIP OPERATION

When a serious fault occurs, the generation of the gas is so rapid that an oil surge is set up through the relay. This oil flow will impinge upon the flap fitted to the trip element causing it to rotate about its axis and so bring the mercury switch to the closed position, which in turn operates the tripping devices.
In the event of serious oil loss from the transformer, both alarm and trip elements operate in turn, in the manner previously described for gas collection. The oil level in the double element relay can be monitored
against a graduated scale on the windows both sides.
SINGLE ELEMENT AND TAP-CHANGER TYPES
Single element type relays are available for 1" bore size, designated 1 SE, which operate indiscriminately for Gas or Oil collection and are suitable for small oil filled transformer, capacitor and potential transformer protection. single element relays can also be used for Tap-Changer type transformers which operate for a surge condition or loss of oil only and allow gas, normally produced during tapchanging operations, to pass freely. The single element relay has only one operating element and operates in a similar manner to that described for the double element types.

8.3 Transformer Breathers

Transformer Breathers eliminate oil thickening and deteriorating when air space above it expands and contracts with climatic variations. Units are filled with self-indicating, environmentally friendly Silicagel adsorbent that changes color when it reaches saturation level. Exhausted cartridge can be changed Transformer Breather Protects Oil and Reduces Maintenance

Transformer breathers, avoid the problem of oil in a conservator tank thickening and deteriorating when the air space above it expands and contracts with climatic variations.

breathers are filled with self-indicating Silicagel adsorbent in a cartridge which should be changes when the color of the gel changes to pink from blue.

Chapter-9

9 THREE-PHASE TRANSFORMERS

9.1 Three Phase Connection

Single-phase transformers can be connected to form three-phase transformer banks. Normally, three nominally identical transformers (P, Q, and R) are used and connected symmetrically (some special cases will be discussed later). The primaries are connected in delta (Δ) or in wye (Y), as are the secondaries. The possible combinations are: Δ-Δ, Δ- Y, Y-Δ and Y – Y . The names come from the appearance of the diagrams we use - see below. A Δ -Y or Y- Δ connection introduces a 30° phase shift and a √3 change in the voltage ratio as will be discussed in detail. We will assume that the individual transformers are ideal in the following sections.

Delta-Delta Connection

The terminal connections are shown in Fig 1 whereas Fig 2 helps us understand the phase relationships. VAB and V12 are the voltages across the primary and secondary of one of the three transformers (P). They are in phase with each other and differ in magnitude by the turns ratio of the transformer. The same is true for the other two transformers.
The currents IP and IS (pri and sec currents of transformer P) are in phase with each other and differ in magnitude by the inverse turns ratio.

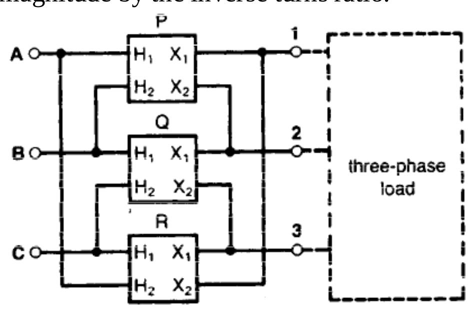


Fig. 9.1

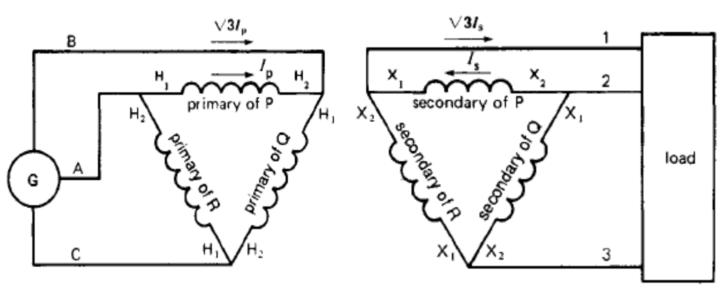


Fig.9.2

There are two sets of currents in a delta connection, the line currents, IL, which flow in and out of the bank, and the currents which flow in the windings (inside the delta) **-** these are called phase or delta currents IΔ. The line currents are √3 larger than the delta currents and are shifted in phase by 30° .

Recall 3-phase circuits notes: $I_L = \sqrt{3}\ \angle{-30}\ I_\Delta$

Sample calculation
A Δ **-** Δ transformer bank drops the utility voltage of 138 kV to 4160 V for a manufacturing plant.
The plant draws 21 MW at 86% lagging.
(a) The apparent power drawn by the plant is: P/PF = 21/0.86 = 24.4 MVA
(b) The apparent power drawn by the transformer bank is: 24.4 MVA *(TFB considered lossless)*
(c) The current in the HV lines is: S/(√3 × VLL) = 24.4 M / (√3 × 138 k) = 102 A
(d) The current in the LV lines is: S/(√3 × VLL) = 24.4 M / (√3 × 4160) = 3384 A
(e) The current in the windings of each TF is: I_HV = 102/√3 = 58.9 A, I_LV = 3384/√3 = 1954 A
(f) The load carried by each TF is: 24.4/3 = 8.13 MVA or using 4160 × 1954 or 138 k × 58.9

Delta-Wye Connection
The connection of the primaries is the same as in the previous case (delta). The secondaries are connected in wye which creates a common neutral point N and two sets of voltages, line-to-line V_{LL} and line-to-neutral V_{LN}. In this case, the primary voltage of transformer P is a line-to-line voltage, and its secondary voltage is line-to-neutral. When we state the voltage ratio of the transformer bank, we compare L-L voltages, so the bank ratio is √3 larger than the individual transformer ratios, and there is a 30° phase shift.

$V_{LL} = \sqrt{3}\ \_\ \angle 30\ V_{LN}$

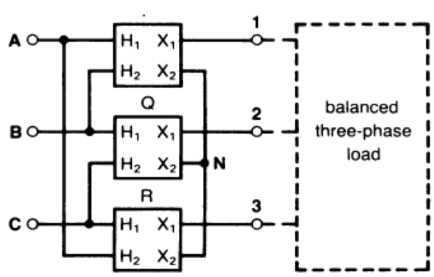


Fig.9.3 Delta-Wye Connection

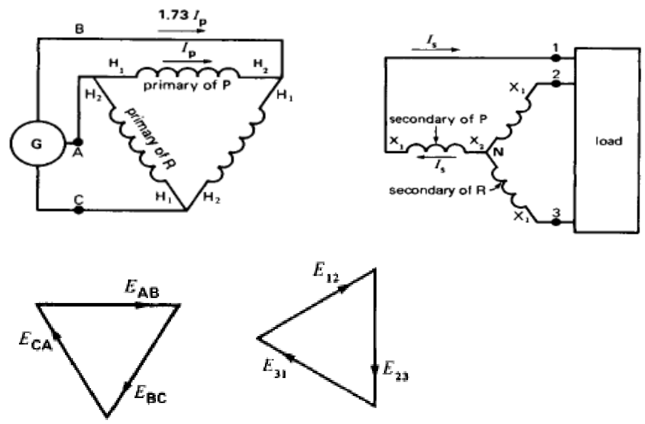


Fig.9.4 Δ -Y Schematic and Voltage Phasors

Since the secondary and the primary voltages of any one transformer are in phase, the bank output voltage must lead the bank input voltage by 30°. This can be seen in the phasor diagram of Fig 4 by comparing E_{12} with $E_{AB.}$

Sample calculation 3 1-phase step-up TFs rated at 40 MVA, 13.2 kV / 80 kV are connected in _-Y and connect a 13.2 kV transmission line to a 90 MVA load. Calculate:
(a) The load voltage: For one TF, VP is 13.2 kV, VS is 80 kV (which is a L-N voltage)
For load or bank, VLOAD (L-L) = √3 × VL_N = √3 × 80 k = 138 kV
(b) The currents in the TF windings: For one TF, S = 90 MVA / 3 = 30 MVA
$I_{PRI\ \Delta} = S / V_{WDG} = S / V_{L-L}$ = 30 M / 13.2 k = 2272 A
$I_{SECY} = S / V_{WDG} = S / V_{L-N}$ = 30 M / 80 k = 375 A
(c) The line currents (LV and HV): I_{LV} =√3 × 2272 = 3932 A *(from delta to line)*
I_{HV} =375 A *(no adjustment in a wye)*

Wye-Delta Connection

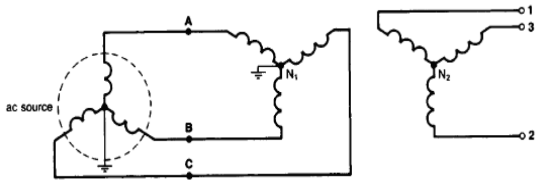
The reverse of the delta-wye connection, the bank ratio is _3 smaller than the individual transformer ratios, and the bank output voltage must lag the bank input voltage by 30_.

Wye-Wye Connection

As with the delta-delta connection, the bank ratio is the same as the individual transformer ratios, and the bank output voltage is in phase with the bank input voltage. The only extra possible problem is that the neutral point may shift causing unbalance of the line-to-neutral voltages. This can be caused by unbalanced loads (different load currents in each of the three phases).

4-Wire Wye Connection

There are two solutions. Use a 4-wire system (see Fig. 12.6) and tie the neutral points together - forcing the line-to-neutral voltage to be balanced, or



Primary Secondary

Fig.9.5 4-Wire Wye Connection

3-Wire Wye with Tertiary

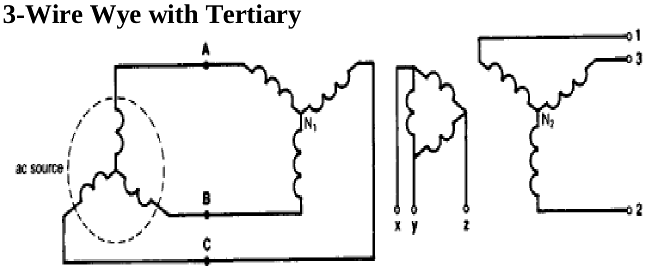


Fig 9.6 Primary Secondary

add a tertiary winding connected in delta (see Fig.9.6) - forcing the voltages to sum to zero.

Calculations involving Three-phase Transformer Banks (6 assumptions)

1. We assume both primary and secondary windings are connected in wye (even if they are not).
2. We consider one single-phase transformer of this assumed Y-Y bank.
3. We consider the primary voltage to be the line-to-neutral voltage of the incoming line.
4. We consider the secondary voltage to be the line-to-neutral voltage of the outgoing line.
5. We consider the nominal power rating to be one-third of the bank rating.
6. We consider the load on this transformer to be one-third of the load on the bank.

Example *3-phase bank is rated at 1300 MVA, 24.5 kV / 345 kV, 60 Hz, XL = 11.5 %.*
This bank connects a 24.5 kV generator to a 345 kV transmission grid
Determine the equivalent circuit and the generator terminal voltage when this transformer delivers 810 MVA at 370 kV with a 90 % lagging power factor.

We use the per-unit method and work on the HV side of the bank using the six assumptions.

VBASE = $345/\sqrt{3}$ = 199.2 kV, SBASE = 1300/3 = 433.3 MVA, ZT = 0 +j 0.115 pu

SLOAD = 810 / 3 = 270 MVA SLOAD (PU) = SLOAD / SBASE = 270 / 433.3 = 0.6231 pu

VLOAD = 370 / $\sqrt{3}$ = 213.6 kV VLOAD (PU) = VLOAD / VBASE = 213.6 / 199.2 = 1.0723 pu

I (PU) = SLOAD (PU) / VLOAD (PU) = 0.6231 / 1.0723 = 0.5811 pu _ = $\cos^{-1}$ 0.90 = 25.84°

V GEN = VLOAD + I×ZT = $1.0723 \angle 0 + (0.5811 \angle -25.84) \times (0.115 \angle 90)$

= $1.0723 + j\,0 + (0.0668 \angle 64.16) = 1.1014 + j\,0.0601 = 1.103$ pu $\angle 3.12°$

VGEN = VGEN (PU) ×VBASE = 1.103 × 24.5 kV = 27.02 kV *(answer is line-to-line on LV side)*

Connections of terminals

When you start making the connections between the transformer's terminals and the incoming and outgoing conductors, carefully follow the instructions given on the nameplate or on the connection diagram. Check all of the tap jumpers for proper location and for tightness. Re-tighten all cable retaining bolts after the first 30 days of service. Before working on the connections make sure all safety precautions have been taken. As appropriate, you should make arrangements to adequately support the incoming/outgoing connecting cables to ensure that there is no mechanical stress imposed on transformer bushings and connections. Such stress could cause a bushing to crack or a connection to fail.

Transformers are usually designed and built to provide good electrical connections using either copper or aluminum cable. A protective plating or compound that prevents surface oxidation on the aluminum terminals is usually applied at the factory. You should not remove this coating from tap and line terminals. Also, when aluminum conductors are used, give them a protective compound treatment at the terminal as specified by the cable manufacturer.

One should follow the instructions provided by the transformer manufacturer. Torque specifications are sometimes listed on the hardware. After applying proper torque, you should wait a minute or so, and then re-tighten all bolts to the specified torque.

You should use commercially available, properly sized, UL-listed mechanical- or compression-type lugs. These terminations should be attached to the cables as specified by the termination or cable manufacturer. Such terminations are available from electrical distributors. Do not install washers between the terminal lugs and the termination bus bar as this will introduce an added impedance and will cause heating and possible connection failure.

Some transformer manufacturers recommend that the cable size be based on an ampacity level of 125% of nameplate rating. When speaking to consulting engineers on this topic, we've found that they recommend the cable be sized for the transformer's nameplate rating. You take your choice; extra safety and extra cost or regular-sized cables. Whatever the choice, the cable insulation rating must be adequate for the installation. The cables you install must be kept as far away as possible from coils and top blades.

9.2 Parallel operation of Power transformer

The need for operation of two or more transformers in parallel often arises due to:

1) Load growth, which exceeds the capactiy of an existing transformer
2) Lack of space (height) for one large transformer
3) A measure of security (the probability of two transformers failing at the same time is very less)
4) The adoption of a standard size of transformer throughout an installation

Conditions necessary for parallel operation

The Polarity or phase sequence is the same
All paralleled units must be supplied from the same network.
The winding configurations (star, delta, zigzag star) of the several transformers

have the same phase change(angle of displacement) between primary and secondary voltages
The short-circuit impedances are equal, or differ by less than 10%
Voltage differences between corresponding phases must not exceed 0.4%
Transformers in parallel must be of equal voltage. If the voltages are not equal, the difference between the voltages will result in a net voltage, which will cause current to circulate on the closed network between the two transformers

The theoretically ideal conditions for paralleling transformers are:
1. Identical turn ratios and voltage ratings.
2. Equal percent impedances.
3. Equal ratios of resistanc to reactance.
4. Same polarity.
5. Same phase angle shift.
6. Same phase rotation

Single-Phase Transformers
For single-phase transformers, only the first four conditions apply, as there is no phase rotation or phase angle shift due to voltage transformation.
If the turns ratio are not same a circulating current will flow even at no load. If the percent impedance or the ratios of resistance to reactance are different there will be no circulating current at no load, but the division of load between the transformers when applied will no longer be proportional to their KVA ratings.

Three-Phase Transformers
The same conditions hold true for three phase transformers except that in this case the question of phase rotation and phase angle shift must be considered.

Phase Angle Shift (Vector groups)
Certain transformer connections as the wye-delta or wye-zigzag produce a 30º shift between the line voltages on the primary side and those on the secondary side. Transformers with these connections cannot be paralleled with other transformers not having this shift such as wye-wye, delta-delta, zigzag-delta, or zigzag-zigzag.

Phase Rotation
Phase rotation refers to the order in which the terminal voltages reach their maximum values. In paralleling, those terminals whose voltage maximums occur simultaneously are paired.

Power Transformer Paralleling
In practice, good paralleling can be accomplished although the actual transformer conditions deviate by small percentages from the theoretical ones.
Paralleling is considered attainable when the percentage impedances of two winding transformers are within 7.5% of each other. For multi-winding and auto-transformers, the generally accepted limit is 10%.
Power transformers of normal design the ratio of resistance to reactance is generally sufficiently small to make the requirement of equal ratios of negligible importance in paralleling.
When it is desired to parallel transformers having widely different impedances, reactors or auto-transformers having the proper ratio should be used. If a reactor is used it is placed in series with the transformer whose impedance is lower. It should have a value sufficient to bring the total effective

percent impedance of the transformer plus the reactor up to the value of the percent impedance of the second transformer.
When an auto-transformer is used, the relative currents supplied by each transformer are determined by the ratio of the two sections of the auto-transformer. The auto-transformer adds a voltage to the

voltage drop in the transformer with the lower impedances and subtracts a voltage from the voltage drop in the transformer with the higher impedance. Auto-transformers for use in paralleling power transformers are specially designed for each installation. The wiring diagram showing the method of connecting the auto-transformer is usually furnished.

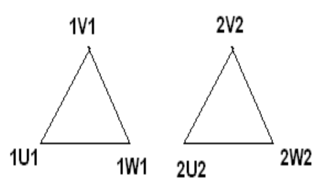
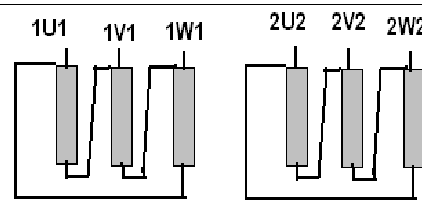
In general, transformers built to the same manufacturing specifications as indicated by the nameplate may be operated in parallel.

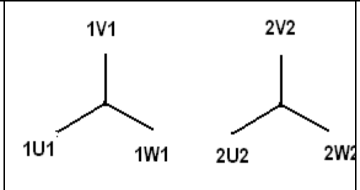
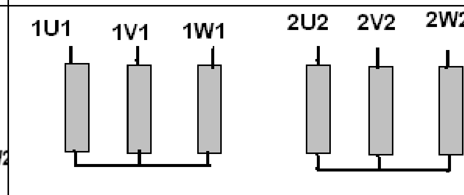
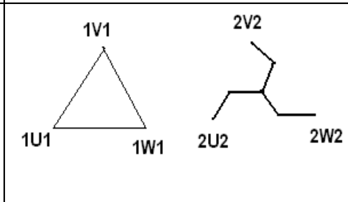
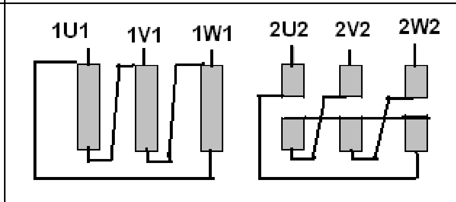
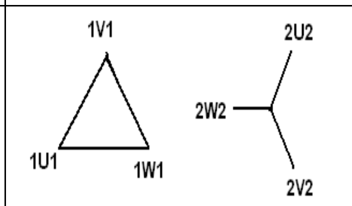
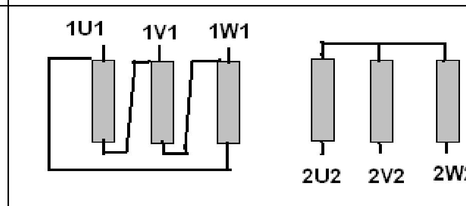
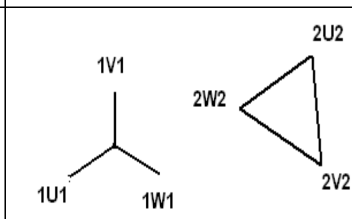
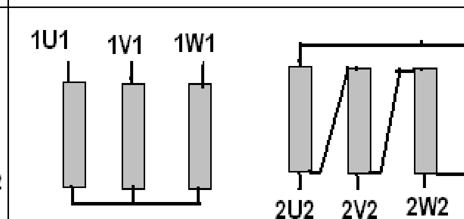
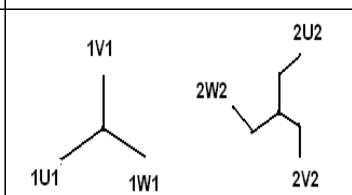
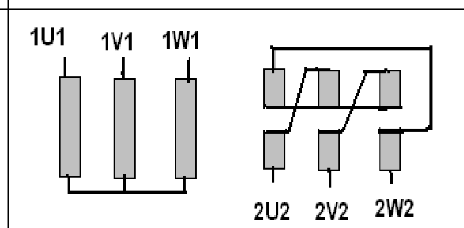
Connecting transformers in parallel when the low voltage tension is comparatively low requires care that the corresponding connecting bars or conductors have approximately the same impedance. If they do not, the currents will not divide properly.

Load Sharing :
The total power (kVA) available when two or more transformers of the same kVA rating are connected in parallel, is equal to the sum of the individual ratings, providing that the percentage impedances are all equal and the voltage ratios are identical.
Transformers of unequal kVA ratings will share a load practically (but not exactly) in proportion to their ratings, providing that the voltage ratios are identical and the percentage impedances (at their own kVA rating) are identical, or very nearly so. In these cases, a total of more than 90% of the sum of the two ratings is normally available. It is recommended that transformers, the kVA ratings of which differ by more than 2:1, should not be operated permanently in parallel.

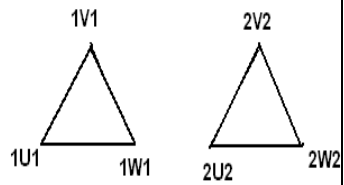
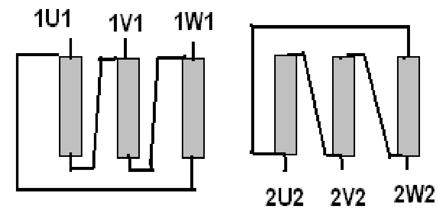
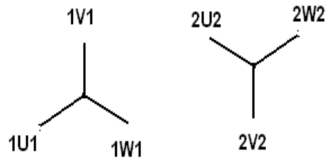
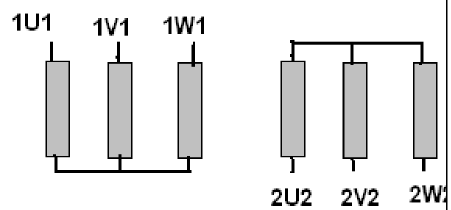
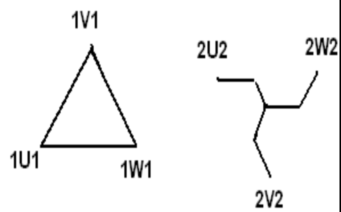
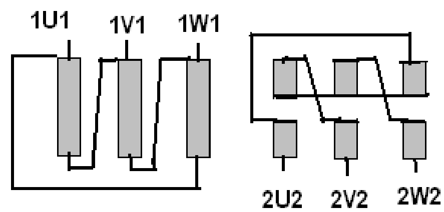
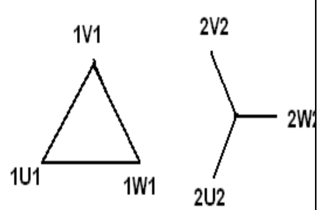
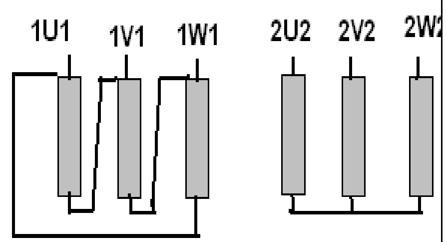
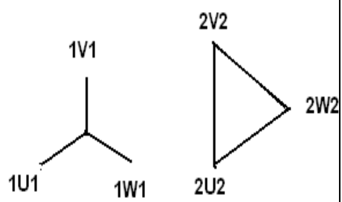
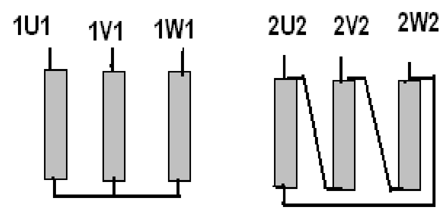
9.3 Vector Groups and Diagrams

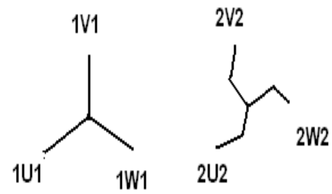
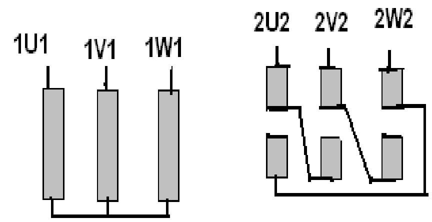
Table 9.1

Code No.	Vector group	Vector Diagram	Circuit Configuration	Secondary Star point
0 (0deg)	Dd0			None

Code No.	Vector group	Vector Diagram	Circuit Configuration	Secondary Star point
	Yy0			10 % load capacity
	Dz0			Full load capacity
5 (120 deg)	Dy5			Full load capacity
	Yd5			None
	Yz5			Full load capacity

Code No.	Vector group	Vector Diagram	Circuit Configuration	Secondary Y -Star point

6 (180 deg)	Dd6			None
	Yy6			10 % Load Capacity
	Dz6			Full load capacity
11 (30 deg lead)	Dy11			Full Load capacity
	Yd11			None
	Vector group	Vector Diagram	Circuit Configuration	Secondary Y -Star point

	Yz11			Full load capacity

9.4 Vector groups and parallel operation

The vector group marks the circuitry of windings and their phase position to each other. It consists of a capital and small letter plus a code number. The capital letter refers to the input winding, the small to the output winding.
The upper voltage is marked by 1 in front, the undervoltage by a 2 in front, regardless of input or output voltage. A 1 in back on the contrary, marks the beginning of a winding, a 2 in back the end. Tabs are marked 3 and 4 in back. The numbers correlate to letters U V W and distinguish the 3 phases.
The neutral point (star point) is always marked N. The most common vector groups are summarized alongside, input
left-hand, output right-hand. Unless otherwise requested, three-phase transformers are preferentially delivered in star-star connection.
If on secondary side, in relation to the primary side, higher currents at smaller voltages are needed, preferentially
Yd5 / Yd11 is used because of the winding cross sections.
The transformers of the same vector group can be operated in parallel by connecting terminals A,B,C on the primary side with terminals a,b,c on the secondary side of the transformers through the respective busbars.
However it is possible to use transformers of vector group (Code 0) in parallel with those in group (Code 6) by suitable internal winding adjustment.

Paralleling operation through Tap changer
Transformers connected in parallel even though of identical ratings will have some difference in impedance leading to unequal load sharing and thereby circulating currents through the windings.
To minimize the unequal loads being shared the Load Tap changer is used to change taps automatically so that the voltage and hence the load on the transformer changes so that the transformers are equally loaded.

Chapter-10

10 TRANSFORMER PROTECTION

Power transformers are the most expensive single elements of HV transmission systems. transformers represent the largest portion of capital investment in transmission and distribution substations. In addition, power transformer outages have a considerable economic impact on the operation of an electrical network

Therefore, it is the aim of Power Engineers to increase the reliability of transformer operation ,usable service life and decrease the transformer maintenance costs

Transformer are subjected to various types of short circuits currents, thermal and transient mechanical stresses which occur during switching operation and on fault hence they need to be isolated during such conditions to avoid insulation failure and abnormal heating of the windings

10.1 Types of protection

The following protection relays / equipment are used depending on the size, importance and construction (tap changer type) of the transformer.

1. HRC fuses
2. Overcurrent protection
3. Graded time lag overcurrent relay
4. Instantaneous earth fault protection
5. Restricted earth fault protection
6. Buchholz relay (Gas operated protection)
7. Differential protection
8. Over-flux protection
9. Over-voltage protection
10. Under voltage protection
11. Surge protection (horn gaps and lightning arrestors)
12. Under-frequency protection

The faults commonly occurring in power transformer are phase to earth , Phase to phase, inter turn winding, overheating of winding due to overcurrents.

In addition transformers are subjected to other causes of failure due to core heating, insulation oil breakdown, improper or insufficient cooling system (circulating oil), winding displacement due to mechanical vibrations, low oil level

The transformer unit protection system (differential) should not operate for faults occurring outside the transformer protection zone. The transformer overload relay is provided as a back up for faults beyond transformer protected zone.

The following details of the transformer are required for selecting the relays and protection scheme

1. KVA rating
2. Voltage ratio
3. type of connection (star-delta ,etc)
4. Dry (resin clad) or Oil filled
5. conservator used or not
6. percentage Impedance
7. Tap changer type
8. Cooling system
9. Neutral Earthing type (solid or through resistor)
10. Connected load

Protective system for distribution transformers :
Small transformers (below 500 KVA) :H.V fuses for phase-earth and phase-phase faults

Graded time lag relays are sometimes used for oveloads
Above 500 KVA or important transformers :
1. Overcurrent relays
2. Instantaneous earth fault relays

For transformers **upto 5 MVA** rating
1. Overcurrent protection
2. Restricted earth fault relay
3. Buchholz relay Over-flux protection

For transformers **above 5 MVA** rating
1.Overcurrent protection
2. Restricted earth fault relay
3. Buchholz relay
4. Over-flux protection
5. Differential protection
6. Sudden pressure relays
7. winding temperature alarm

Table 10.1

Type of Fault	**Protection device used**
Overloads (thermal)	Thermal overload relays Temperature relays alarms
Overcurrents sustained (overload)	Graded time lag overcurrent relays
Through faults (back up protection)	Time graded overcurrent relay HRC fuses (small transformers)
High voltage surges (Lightning and switching)	Lightning Arrestors, rod gap
Heavy internal faults (phase to ground, phase to earth)	Buchholz relay trip action
Incipient faults (interturn short circuit, winding insulation breakdown, oil insulation breakdown)	Buchholz relay alarm action Sudden pressure relay Pressure relief valve
Earth faults	Earth fault relay Diffrential protection
Magnetic saturation of core	Overflux relay Overvoltage relay

10.2 Thermal Overload protection

For liquid-immersed power transformers, the temperature of the winding hot-spot is the important factor in the long-term life of the transformer. The insulating oil temperature is dependent on the winding temperature, and is used to indicate the operating conditions of the transformer. Failure to limit these temperature rises to the thermal capability of the insulation and core materials can cause premature failure of the transformer.

Thermal Protection Functions

THERMAL protection functions can be discussed in several broad groups. The first group is "mechanical", in that physical sensors and relays attempt to detect over-temperatures, and take mitigating action through alarms and tripping. These types of protection functions include direct temperature sensors, internal thermal relays, sudden pressure relays, and gas detection relays. It is important to note that the temperature sensors work almost exclusively on top-oil temperature. An important part of this type of protection is the transformer cooling system, as different stages of cooling fans and pumps are started by temperature sensors. Some transformers also use a topoil temperature monitor that includes contacts that can directly be used for alarming and tripping on oil temperature.

A second group is overcurrent based overload protection, provided by fuses or overcurrent relays. These devices operate when current exceeds a value that is an unacceptable overload on the transformer. This overload will cause oil temperature rise, so the overload functions provide limited thermal protection by de-energizing the transformer.

Thermal Overload function available in modern numerical transformer protection relays acts depending on the specific implementation in the relay, uses some combination of measured current, ambient temperature, and transformer oil temperature to detect the presence of an over-temperature condition. The function can then alarm the presence of an over-temperature condition, remove load from the transformer, or trip the transformer off-line.

Table 10.2

Standard temperature limits		
Average winding temperature rise	65º C	Above ambient
Hot-spot temperature rise	80º C	Above ambient
Top liquid temperature rise	65º C	Above ambient
Maximum temperature limit	110º C	Absolute

Table 10.2: Standard temperature limits, 65º C rise transformer, 30º ambient temperature

Typical settings for oil temperature are
60 deg C - Switch on Fans
95 deg C - Alarm
120 deg C – Trip

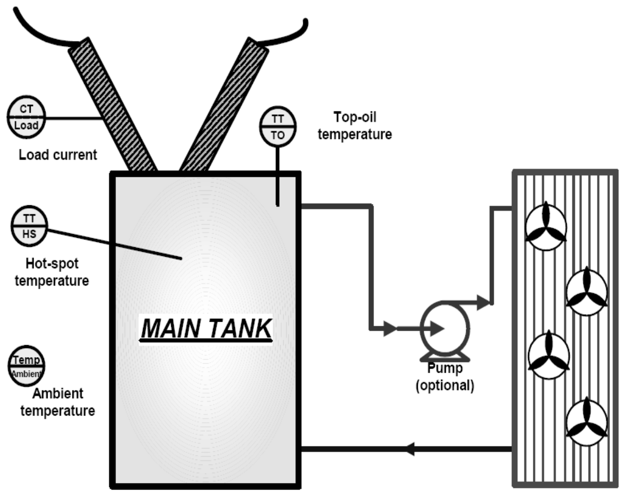


Fig.10.1 Temperature measurement

Measuring Ambient Temperature

TRANSFORMER operating temperatures are based on rise above ambient temperature. Models of transformer oil temperatures generally require directly measuring the ambient temperature to determine the operating state of the transformer. For example, as previously defined, the hot-spot oil temperature is directly dependent on the ambient temperature. So the major advantage of measuring the ambient temperature is improving the accuracy of top-oil temperature calculations, and hot-spot temperature calculations. Measuring the ambient temperature requires connecting a temperature probe to the relay. Temperature probes traditionally use a transducer output, but may use RTD (Resistor Temperature Detector) connections in some instances.

Measuring Top-Oil Temperature

TOP-OIL temperature is easily measured. Suitable top-oil temperature sensors are installed as part of the transformer cooling system. The actual temperature sensor is usually an RTD mounted in a heated thermowell in one phase of the transformer. Top-oil temperature sensors are also easy to install, as sensors that mount externally to the tank are available. Directly measuring the top-oil temperature improves the accuracy of temperature based protection functions, and improves the accuracy of hot-spot temperature calculations.

Use of measured top-oil temperature does require a temperature sensor at the transformer, with a physical connection to the transformer protection relay. With newer transformer installations, the top-oil temperature may be an output of the transformer cooling controls. Measuring the top-oil temperature at only one point assumes some homogeneity among the oil temperature in the transformer tank. It is possible to use multiple sensors for per-phase measurements of top-oil temperature, and therefore per-phase temperature protection of the transformer. However, the top-oil temperature will be identical between all three phases, unless there is significant load imbalance.

Measuring Hot-Spot Temperature

The aim of temperature-based transformer protection is to limit the impact of the hottest-spot temperature on transformer winding insulation. Therefore, using measured hot-spot temperature provides the most accurate protection against transformer over-temperature conditions, and may be the only measurement required for protection purposes. The biggest disadvantage to this method is the hot-spot temperature sensor. Practically, the sensor must be installed during manufacture of the transformer, as the sensor must be physically installed in the transformer winding at a point calculated by the transformer designer to be the location of the hot-spot. As the temperature sensors must also be electrically isolated from the transformer tanks and windings, hot-spot temperature sensors are typically fiber-optic sensors. These sensors are installed to measure the hot-spot temperature, for large power transformers.

Oil & Winding Temperature Indicator

Oil temperature indicators are generally of two types, one with rigid stem and the other type with capillary tube. They are fitted with temperature sensing elements at the end of rigid stem or capillary tube.

Winding temperature Indicator is provided with capillary tube with sensing element (bulb) at the end of tube. Sensing elements are enclosed in metal bulb, which are fitted in pockets provided on tank over in the hottest oil region.

Before inserting temperature sensing bulb inside the pocket, transformer oil or heat conducting grease should be filled in pocket. The union coupling on the bulb should be screwed tightly on the pocket so that water does not penetrate inside the pocket.

Capillary tube of instrument must be routed and fixed such a way that it suffers less risk of being pinched or bent or cut off. Plastic straps are provided with each instrument for fixing the tube. Surplus length of tube should not be cut off since the pressure balanced system will be destroyed. Tube may be made into loop more than 150 mm diameter and tied to tank in suitable position. Utmost care should be taken while fitting sensing bulb in the pocket since it is likely that capillary tube may form sharp bends and damage the instrument.

Instruments are calibrated and under no circumstances indicator pointer should be moved by hand or bent, as it might suffer permanent damage. If the instrument is not giving correct temperature indication as a result of improper handling or any other cause, it may be calibrated as given in instrument’s pamphlet.

Winding temperature indicator (with a separate heater pocket) . Temperature sensing bulb provided at the end of capillary should be fitted in the heater pocket in housing fitted on tank cover. Two terminals provided in housing are connected to the heating coil of heater pocket inside the housing (outside tank) and to current transformer secondary terminals from the inside of tank. (These are normally connected before dispatch of transformer). Housing is air filled. Instrument is housed in the marshalling box

10.3 Over-flux protection

When the operating system frequency raises above the rated transformer frequency, the working magnetic flux in the core and windings increases thereby increasing iron and core loses and heating up the core lamination stressing the lamination insulation.

The over-flux relay operates on the V/F input, where voltage is fed from the voltage transformer and frequency from the supply.

Over-flux relay is set with sufficient time lag

10.4 Transformer differential protection

Percentage-restraint differential protective relays are used as a proven fast acting protection for power transformers and have been in service for many years.
Figure 10.2 shows a typical differential relay connection diagram.

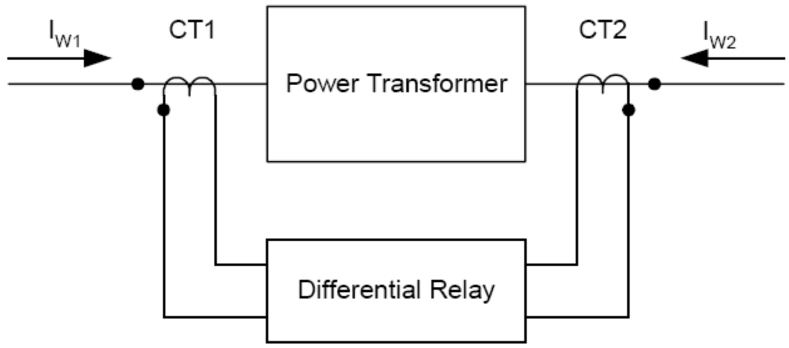


Fig.10.2 Typical Differential Relay Connection Diagram

Differential elements compare an operating current with a restraining current. The operating current (also called differential current), I_{OP}, can be obtained as the phasor sum of the currents entering the protected element:

$$I_{OP} = \left|\vec{I}_{W1} + \vec{I}_{W2}\right|$$

I_{OP} is proportional to the fault current for internal faults and approaches zero for any other operating (ideal) conditions.
There are different alternatives for obtaining the restraining current. The most common ones include the following:

$$I_{RT} = k\left|\vec{I}_{W1} - \vec{I}_{W2}\right|$$

$$I_{RT} = k\left(\left|\vec{I}_{W1}\right| + \left|\vec{I}_{W2}\right|\right)$$

$$I_{RT} = Max\left(\left|\vec{I}_{W1}\right|, \left|\vec{I}_{W2}\right|\right)$$

Where k is a compensation factor, usually taken as 1 or 0.5.
Equation 3 and Equation 4 offer the advantage of being applicable to differential relays with more than two restraint elements.
The differential relay generates a tripping signal if the operating current, *IOP*, is greater than a percentage of the restraining current, I_{RT}:

$$I_{OP} > SLP \cdot I_{RT}$$

Figure10.3 shows a typical differential relay operating characteristic. This characteristic consists of a straight line having a slope equal to SLP and a horizontal straight line defining the relay minimum pickup current, *IPU*. The relay operating region is located above the slope characteristic (Equation 5), and the restraining region is below the slope characteristic. In addition, the slope characteristic of the percentage-differential relay provides further security for external faults with CT saturation. A variable-percentage or dual-slope characteristic, originally proposed by Sharp and Glassburn, further increases relay security for heavy CT saturation. Fig.10.3 shows this characteristic as a dotted line.

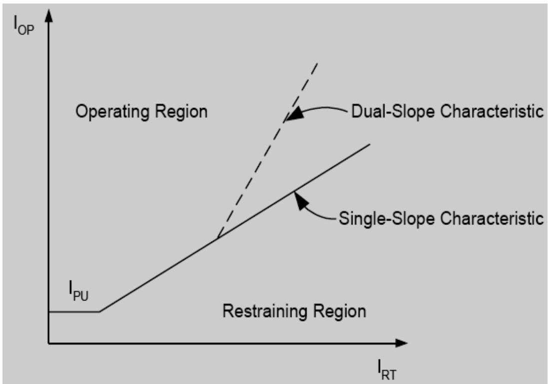


Fig.10.3 A percentage differential relay

SOURCES OF FALSE DIFFERENTIAL RELAY OPERATION

Inrush or overexcitation conditions of a power transformer produce false differential currents that could cause differential relay misoperation. Both conditions produce distorted differential currents because they are related to transformer core saturation. The distorted waveforms provide information that helps to discriminate inrush and overexcitation conditions from internal faults. However, this discrimination can be complicated by other sources of distortion such as CT saturation, nonlinear fault resistance, or system resonant conditions.
In the case of power transformer applications, possible sources of false differential currents are:
• Mismatch between the CT ratios and the power transformer ratio
• Variable ratio of the power transformer caused by a tap changer
• Phase shift between the power transformer primary and secondary currents for delta-wye connections
• Magnetizing inrush currents
• Transformer overexcitation
• Current transformer saturation

The relay percentage restraint characteristic typically solves the first two sources of error mentioned earlier. A proper connection of the CTs or emulation of such a connection in a digital relay addresses the phase shift problem. A very complex problem is that of discriminating internal fault currents from the false differential currents caused by magnetizing inrush and transformer over-excitation.

Inrush Currents
Magnetizing inrush occurs in a transformer whenever the polarity and magnitude of the residual flux do not agree with the polarity and magnitude of the ideal instantaneous value of steady-state flux. Transformer energization is a typical cause of inrush currents, but any transient in the transformer circuit may generate these currents. Other causes include voltage recovery after the clearance of an external fault or the energization of a transformer in parallel with a transformer that is already in

service. The magnitudes and waveforms of inrush currents depend on a multitude of factors, and are almost impossible to predict. The
following summarizes the main characteristics of inrush currents:

• Generally contain d.c. offset, odd harmonics, and even harmonics.
• Typically composed of unipolar or bipolar pulses, separated by intervals of very low current values.
• Peak values of unipolar inrush current pulses decrease very slowly. Time constant is typically much greater than that of the exponentially decaying d.c. offset of fault currents.
• Second-harmonic content starts with a low value and increases as the inrush current decreases.

Transformer Overexcitation

The magnetic flux inside the transformer core is directly proportional to the applied voltage and inversely proportional to the system frequency. Overvoltage and/or underfrequency conditions can produce flux levels that saturate the transformer core. These abnormal operating conditions can exist in any part of the power system, so any transformer may be exposed to overexcitation. Overexcitation of a power transformer is a typical case of a.c. saturation of the core that produces odd harmonics in the exciting current. The third harmonic is the most suitable for detecting overexcitation conditions, but either the delta connection of the CTs or the delta connection compensation of the differential relay filters out this harmonic. The fifth harmonic, however, is still a reliable quantity for detecting overexcitation conditions.
Transformer overexcitation causes transformer heating and increases exciting current, noise, and vibration. A severely overexcited transformer should be disconnected to avoid transformer damage. Because it is difficult, with differential protection, to control the amount of overexcitation that a transformer can tolerate, transformer differential protection tripping for an overexcitation condition is not desirable. A separate transformer overexcitation element, such as a V/Hz element, that responds to the voltage/frequency ratio could be used instead.

CT Saturation

The effect of CT saturation on transformer differential protection is double-edged. For external faults, the resulting false differential current may produce relay misoperation. In some cases, the percentage restraint in the relay addresses this false differential current. For internal faults, the harmonics resulting from CT saturation could delay the operation of differential relays having harmonic restraint or blocking.

The main characteristics of CT saturation are the following:
• CTs reproduce faithfully the primary current for a given time after fault inception. The time to CT saturation depends on several factors, but is typically one cycle or longer.
• The worst CT saturation is produced by the d.c. component of the primary current. During this d.c. saturation period, the secondary current may contain d.c. offset and odd and even harmonics.
• When the d.c. offset dies out, the CT has only a.c. saturation, characterized by the presence of odd harmonics in the secondary current Differential relays perform well for external faults, as long as the CTs reproduce the primary currents correctly. When one of the CTs saturates, or if both CTs saturate at different levels, false operating current appears in the differential relay and could cause relay mal-operation.
Some differential relays use the harmonics caused by CT saturation for added restraint and to avoid mal-operations.

CURRENT-TRANSFORMER CONNECTIONS FOR DIFFERENTIAL RELAYS

A simple rule of thumb is that theCT'S on any wye winding of a power transformer should be connected in delta, and theCT'S on any delta winding should be connected in wye.
This rule may be broken, but it rarely is;
problem is how to make the required interconnection between theCT'S and the differential relay.
Two basic requirements that the differential-relay connections must satisfy are: (1) the differential relay must not operate for load or external faults; and (2) the relay must operate for severe enough internal faults.
If one does not know what the proper connections are, the procedure is first to make the connections that will satisfy the requirement of not tripping for external faults. Then, one can test the connections for their ability to provide tripping for internal faults.
The power transformers are grouped according to the phase displacement as given below
Group 1 :Start – Start, Phase displacement = 0°
Group 2 :Start – Start, Phase displacement = 180°
Group 3 :Delta – Start, Phase displacement = - 30°
Group 4 :Delta – Start, Phase displacement = +30°

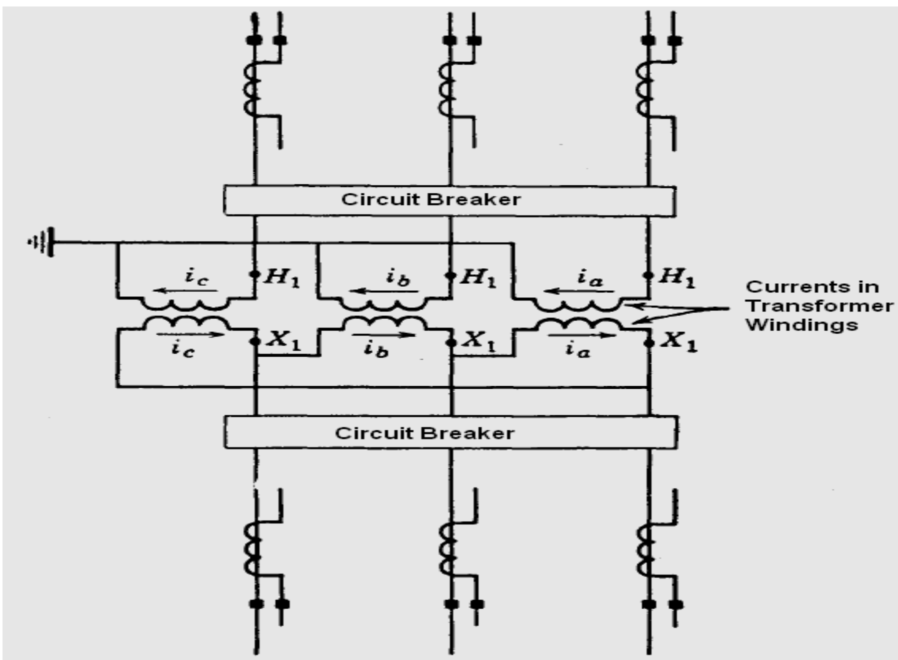


Fig.10.4. Development of CT connections for transformer differential relaying -1

As an example, let us take the wye-delta power transformer of Fig.10.4 The first step is arbitrarily to assume currents flowing in the power-transformer windings in whichever directions one wishes, but to observe the requirements imposed by the polarity marks that the currents flow in opposite directions in

the windings on the same core, as shown in Fig. 10.4 We shall also assume that all the windings have the same number of turns so that the current magnitudes are equal, neglecting the very small exciting-current component.
(Once the proper connections have been determined, the actual turn ratios can very easily be taken into account.)
On the basis of the foregoing, Fig.10.5 shows the currents that flow in the power-transformer leads and the CT primaries for the general external-fault case for which the relay must not trip. We are assuming that no current flows into the ground from the neutral of the wye winding; in other words, we are assuming that the three-phase currents add vectorially to zero.
The next step is to connect one of the sets ofCT'S in delta or in wye, according to the rule of thumb already discussed; it does not matter how the connection is made, i.e., whether one way or reversed.

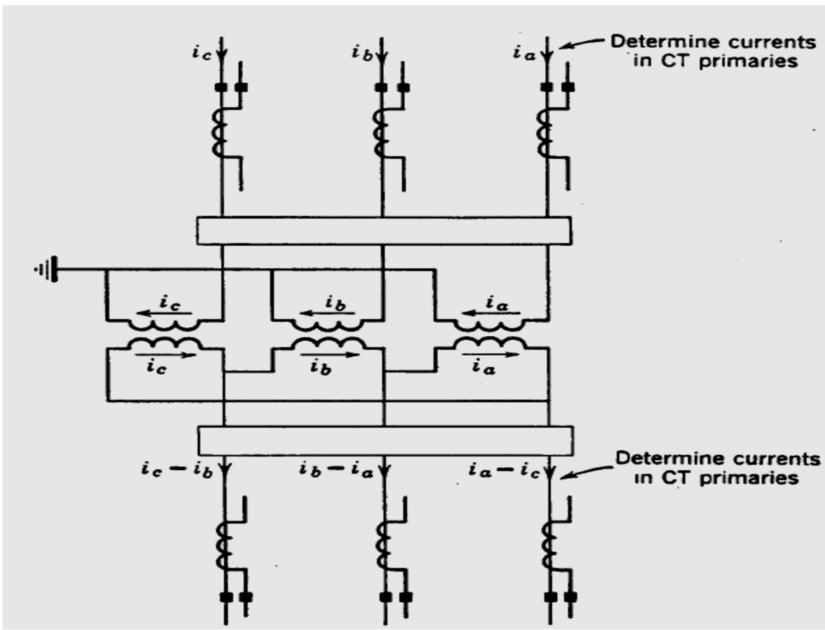


Fig. 10.5 Development of CT connections for transformer differential relaying.-2

Then, the other set of CT's must be connected also according to the rule, but, since the connections of the first set of CT's have been chosen, it does matter how the second set is connected; this connection must be made so that the secondary currents will circulate between the CT's as required for the external-fault case. A completed connection diagram that meets the requirements is shown in Fig.10.6. The connections would still be correct if the connections of both sets of CT's were reversed. Proof that the relay will tend to operate for internal faults will not be given here, but the reader can easily satisfy himself by drawing current-flow diagrams for assumed faults. It will be found that protection is provided for turn-to-turn faults as well as for faults between phases or to ground if the fault current is high enough.

We shall now examine the rule of thumb that tells us whether to connect theCT'S in wye or in delta. Actually, for the assumption made in arriving at Fig.10.5, namely, that the threephase currents add vectorially to zero, we could have used wye-connected CT'S on the wye side and delta-connectedCT'S on the delta side. In other words, for all external-fault conditions except ground faults on the wye side of the bank, it would not matter which pair of CT combinations was used. Or, if the neutral of the power transformer was not grounded, it would not matter. The significant point is that, when ground current can flow

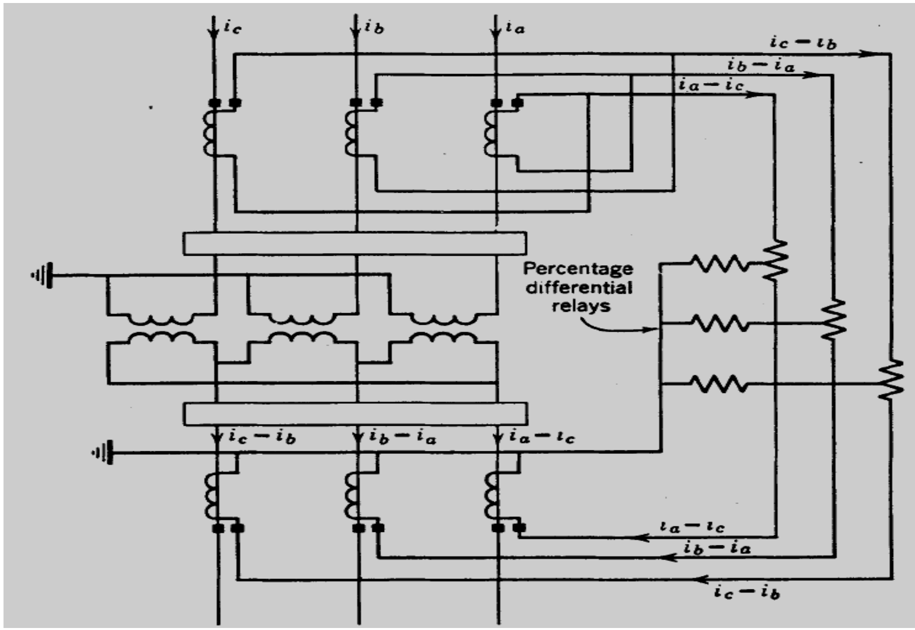


Fig.10.6 Completed connections for percentage-differential relaying for two-winding transformer.

in the wye windings for an external fault, we must use the delta connection (or resort to a zero-phase-sequence-current-shunt that will be discussed later). The delta CT connection circulates the zero-phase-sequence components of the currents inside the delta and thereby keeps them out of the external connections to the relay. This is necessary because there are no zero-phase-sequence components of current on the delta side of the power transformer for a ground fault on the wye side; therefore, there is no possibility of the zero-phase-sequence currents simply circulating between the sets of CT'S and, if the
CT's on the wye side were not delta connected, the zero-phase-sequence components would flow in the operating coils and cause the relay to operate undesirably for external ground faults.

Incidentally, the fact that the delta CT connection keeps zero-phase-sequence currents out of the external secondary circuit does not mean that the differential relay cannot operate for single-phase-to-ground faults in the power transformer; the relay will not receive zerophase- sequence components, but it will receive and operate on the positive- and negative-phase-sequence components of the fault current.

The foregoing instructions for making the CT and relay interconnections apply equally well for power transformers with more than two windings per phase; it is only necessary to consider two windings at a time as though they were the only windings. For example, for three-winding transformers consider first the windings H and X. Then, consider H and Y, using the CT connections already chosen for the H winding, and determine the connections of the Y CT'S. If this is done properly, the connections for the X and Y

windings will automatically be compatible.
Figure 10.7 shows schematic connections for protecting the main power transformer and the station-service power transformer where a generator and its power transformer operate as a unit. To simplify the picture, only a one-line diagram is shown with the CT and power transformer connections merely indicated. It will be noted that one restraint coil is supplied by current from the station-service-bus side of the breaker on the low-voltage side of the station-service power transformer in parallel with the CT in the neutral end of the
generator winding; this is to obtain the advantage of overlapping adjacent protective zones

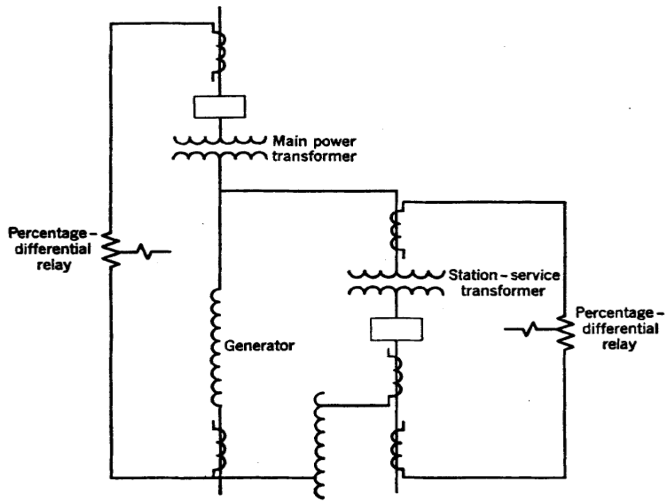


Fig. 10.7 Schematic connections for main and station-service-transformer protection.

around a circuit breaker, as explained in Chapter 1. A separate differential relay is used to protect the station-service power transformer because the relay protecting the main power transformer is not sensitive enough to provide this protection; with a steam-turbine generator, the station-service bank is no larger than about 10% of the size of the main bank, and, consequently, the CT'S used for the main bank have ratios that are about 10 times as large as would be desired for the most sensitive protection of the station-service

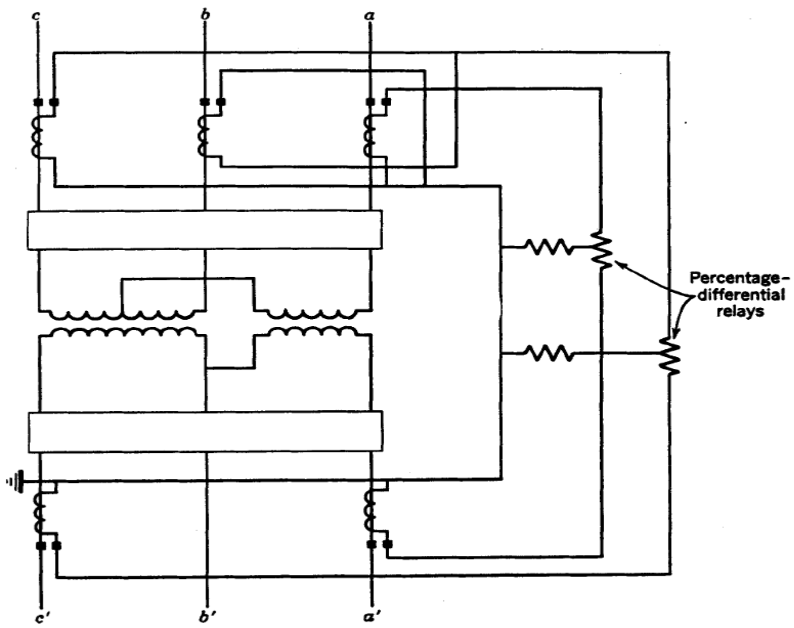


Fig.10.8 Usual method of protecting a Scott-connected bank.

transformer. With a hydroelectric-turbine generator, the station-service transformer is more nearly 1% of the size of the main transformer; consequently, the impedance of the station-service transformer is so high that a fault on its low-voltage side cannot operate the relay protecting the main transformer even if theCT'S are omitted from the low-voltage side of the station-service transformer; therefore, for hydroelectric generators it is the practice to omit these CT'S and to retain separate differential protection for the station service bank. In order to minimize the consequential damage should a station-service-transformer fault occur, separate high-speed percentage-differential relaying should be- used on the station-service transformer as for the main power transformer.

Figure 10.8 shows the usual way to protect a Scott-connected bank. This arrangement would not protect against a ground fault on phase b', but, since this is on the low-voltage side where a ground-current source is unlikely, such a possibility is of little significance. A more

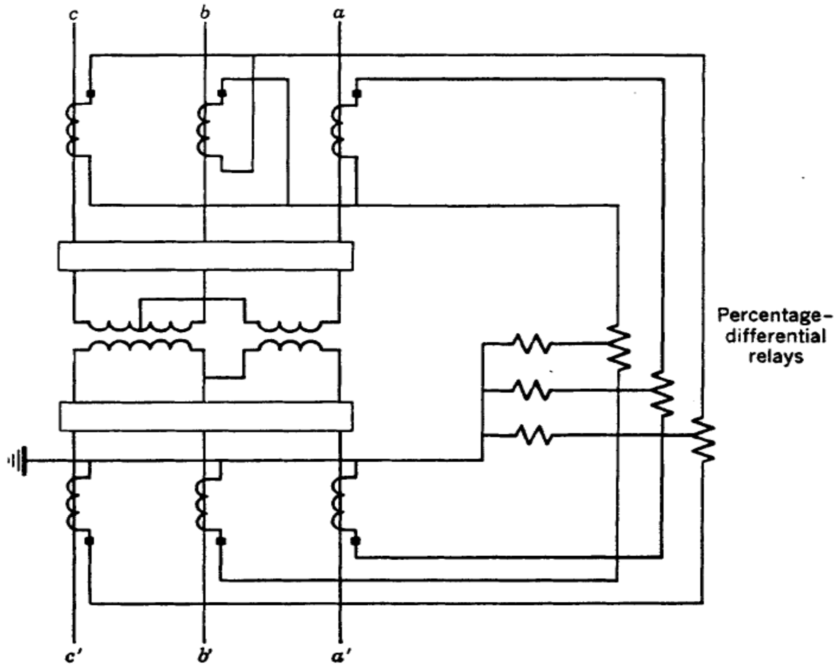


Fig.10.9 Alternative protection of a Scott-connected bank.

practical objection to Fig. 10.8, but still of secondary significance, is that, for certain turn-to turn or phase-to-phase faults, only one relay unit can operate. This is contrasted with the general practice of providing three relay units to protect three-phase banks where, for any phase-to-phase fault, two relay units can operate, thereby giving double assurance that at least one unit will cause tripping. However, since Scott-connected banks are used only at or near the load, it is questionable if the added cost of slightly more reliable protection can be justified. An alternative that does not have the technical disadvantages of Fig. 5 is shown in Fig. 10.9.

Differentially connected CT's should be grounded at only one point. If more than one set of wye-connected CT's is involved, the neutrals should be interconnected with insulated wire and grounded at only one point. If grounds are made at two or more different points, even to a low-resistance ground bus, fault currents flowing in the ground or ground bus may produce large differences of potential between the CT grounds, and thereby cause current to flow in the differential circuit. Such a flow of current might cause undesired tripping by the differential relays or damage to the circuit conductors.

10.5 Protection of parallel transformer

When parallel transformer banks having individual breakers are located some distance away from any generating station, a possibly troublesome magnetizing-current-inrush problem may arise.11 If one bank is already energized and a second bank is then energized, magnetizing-current inrush will occurÐnot only to the bank being energized but also to the bank that is already energized. Moreover, the inrush current to both banks will decay at a much slower rate than when a single bank is energized with no other banks in parallel.

The magnitude of the inrush to the bank already connected will not be as high as that to the bank being switched, but it can easily exceed twice the full-load-current rating of the bank; the presence of load on the bank will slightly reduce its inrush and increase its rate of decay.

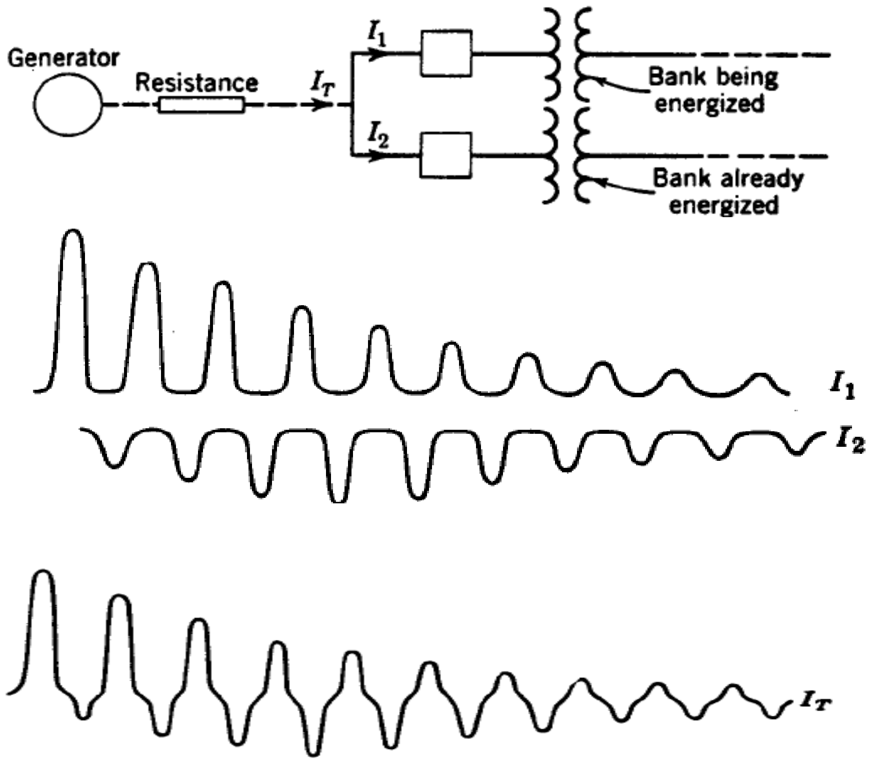


Fig.10.10 Prolonged inrush currents with parallel transformers.

Briefly, the cause of the foregoing is as follows: The d-c component of the inrush current to the bank being energized flows through the resistance of transmission-line circuits between the transformer banks and the source of generation, thereby producing a d-c voltage-drop component in the voltage applied to the banks. This d-c component of voltage causes a build-up of d-c magnetizing current in the already-connected bank, the rate of which is the same as the rate at which the d-c component of magnetizing current is decreasing in the bank just energized. When the magnitudes of the d-c components in both banks become equal, there is no d--c component in the transmission-line circuit feeding the banks, but there is a d-c component circulating in the loop circuit between the banks. The time constant of this trapped d--c circulating current, depending only on the constants of the loop circuit, is much longer than the time constant of the d-c component in the transmission-line circuit feeding the banks. Figure 10.10 shows the circuits involved and the magnetizing-current components in each circuit.

The significance of the foregoing is two-fold. First, desensitizing means already described for preventing differential-relay operation on magnetizing-current inrush are not effective in the bank that is already energized. Only time delay in the operation of the differential relay will be elective in preventing undesired tripping. However, if the banks are protected by separate relays having tripping suppression or harmonic restraint, no undesired tripping will occur.

EXTERNAL-FAULT BACK-UP PROTECTION

A differentially protected transformer bank should have inverse relays, preferably energized from CT's other than those associated with the differential relays, to trip faultside breakers when external faults persist for too long a time. An exception is the transformer bank of a unit generator-transformer arrangement where the generator's external-fault back-up relays provide all the necessary back-up protection. The back-up relays should preferably be operated from CT's located as in Fig. 10.11; this makes it unnecessary to adjust the relays so as not to operate on magnetizing-current inrush and hence permits greater sensitivity and speed if desired. When the transformer is connected to more than one source of short-circuit current, backup relays in all the circuits are required, and at least some may need to be directional, as indicated in Fig. 15, for good protection and selectivity. Each set of back-up relays should trip only its associated breaker, also as indicated in Fig. 15.

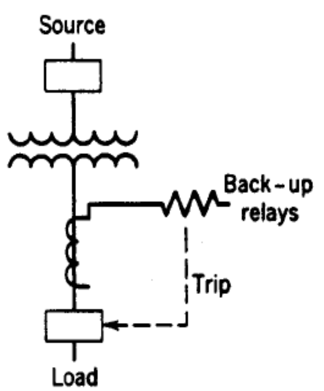


Fig. 10.11 Back-up relaying for transformer connected to one source

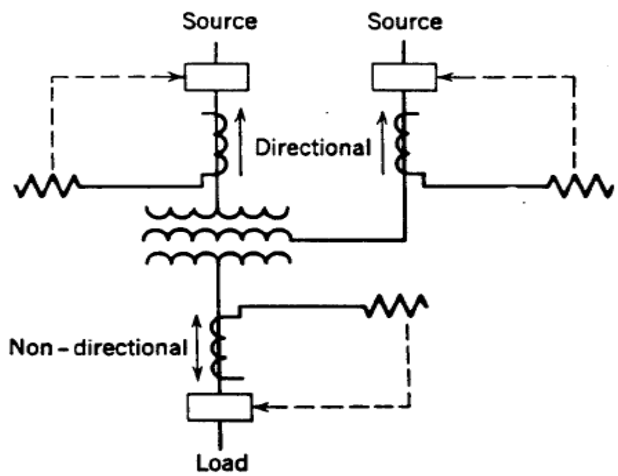


Fig. 10.12. Back-up relaying with two sources.

When a transformer has overcurrent relaying for short-circuit protection because the cost of differential relaying cannot be justified, the same overcurrent relays are used for back-up protection. It is realized that combining the two functions may work to the disadvantage of one or both, but this is the price that one must pay to minimize the investment.

10.6 Internal Fault Protection

Gas Operated Relays

During in transformer internal faults below oil level, the arc produced causes decomposition of transformer oil. The gases formed by decomposition are gathered in the air cushion of the conservator of the transformer.

The rate of gas developed depends on the arc voltage and fault current, the fault may be inter-turn, earth – phase or phase to phase fault and it can be used to detect the fault, the following devices are used.

-pressure relief device
- rate of rise preassure device
- buchholz relay (Gas accumulator device)

Pressure relief relay

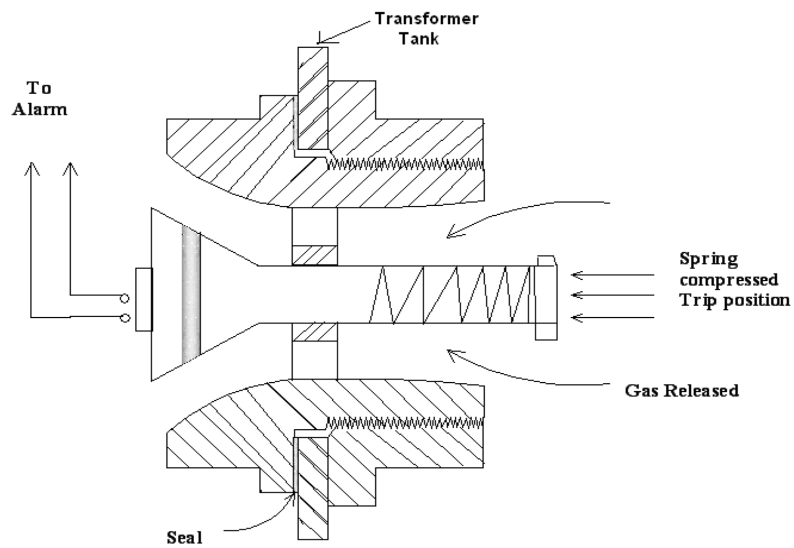


Fig.10.13 Pressure relief relay normal position

The pressure and pressure relief relay is mounted on the transformer tank and operates to release gas to the atmosphere during the following gassing conditions.
- high overload peaks
- prolonged overloads
- arcing faults within oil

The pressure relief valve is a spring loaded device and has a seal-seat (Fig. 10) when the preassure inside the tank increases above a certain set value the force on the movable lever exceeds the spring restraining force and the lever moves forward and closes the alarm contacts and also opens a valve to release pressure.

The relay has to be reset manually after it operates.

Rate –of – rise pressure relay

This relay operates on sudden pressure rise due to heavy internal arcing and not on static or slow pressure build up, The main pressure component is a pressure actuated micro-switch inside a metallic bellow. Static pressure do not compress the bellow ,dynamic pressure pushes the below and operates the micro-switch as shown in fig. 11

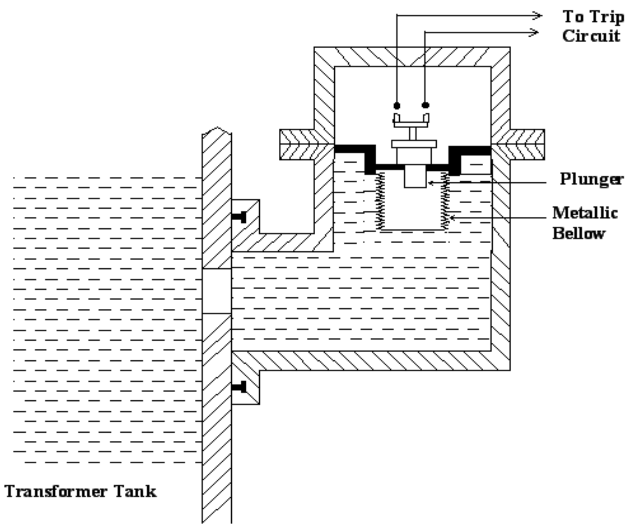


Fig.10.14 Rate of rise pressure relay

Buchholz Relay

Most faults in an oil filled Transformer are accompanied by the generation of gas. By using a suitable relay the formation of this gas can be used as a warning of a developing fault. Double element relays can be used

for detecting minor or major faults. The alarm element will operate after a specified volume of gas has collected to give an alarm indication.

Examples of incipient faults are:

a. Broken-down core bolt insulation

b. Shorted laminations

c. Bad contacts

d. Overheating of part of the windings

The alarm element will also operate in the event of oil leakage or if air enters the cooling system. The trip element will be operated by an oil surge in the event of more serious faults such as:

a. Earth faults

b. Winding short circuits

c. Puncture of bushings

d. Short circuits between phases

The trip element will also operate if a rapid loss of oil occurs.

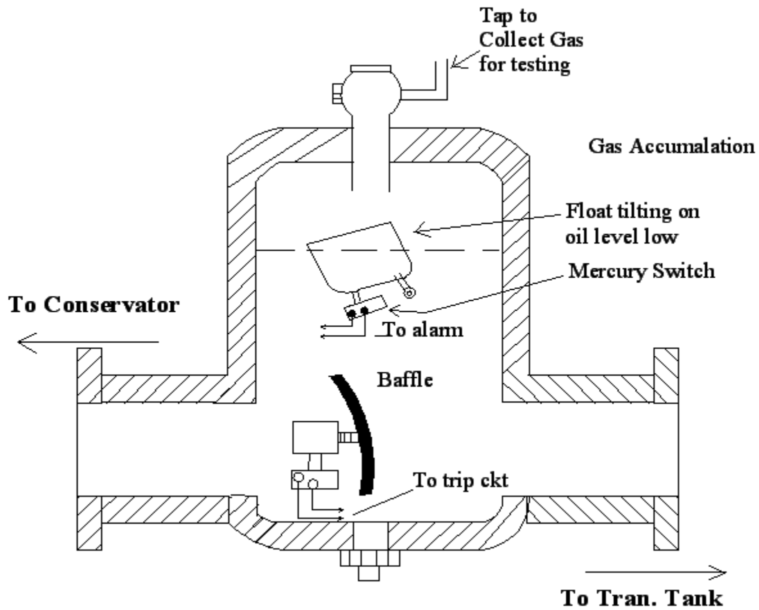


Fig.10.15 Buchholz Relay

MOUNTING POSITION

The relay should be mounted in the connecting pipe between the transformer and the conservator tank. This pipe should be as long and as straight as possible, and must be arranged to slope upwards, towards the conservator, at an angle within the limits of 3 to 7 degrees to the horizontal.

There should be a straight run on the transformer side of the relay of at lease five times the internal diameter of the pipe, and at least three times this diameter on the conservator side.

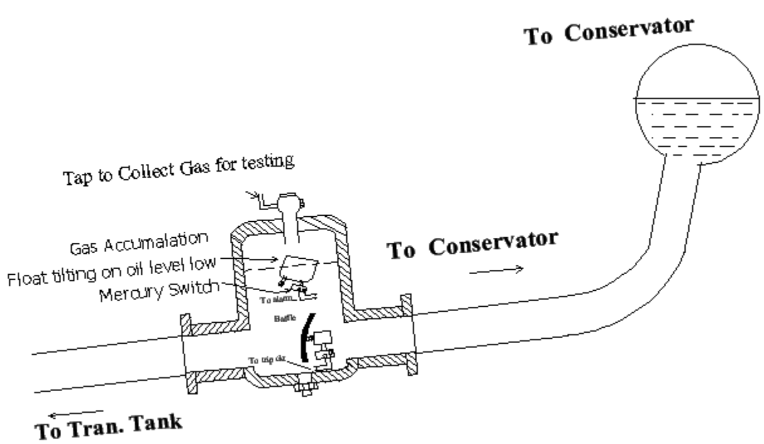


Fig.10.16 Mounting position

CONSTRUCTION AND METHOD OF OPERATION

The relay consists of a lightweight container fitted with two pivoted elements. It is situated in the pipe line between the transformer and the conservator tank, so that under normal conditions it is full of oil. The operating force relies upon the principle that when a body is immersed in a liquid it appears to lose weight.

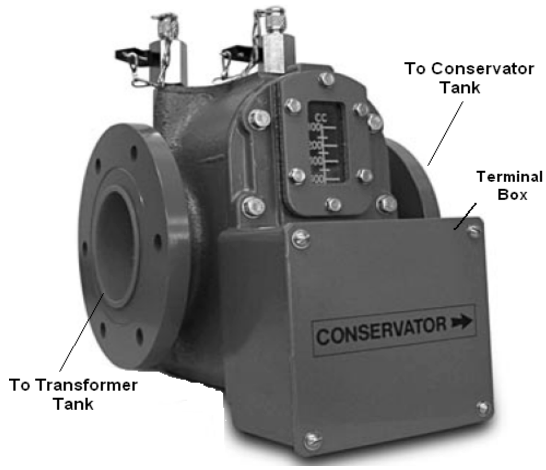


Fig.10.16 Buchholz Relay

Mercury Switches

Mercury switches are employed of a special design to prevent mal-operation due to excessive transformer vibration. A sample relay of this type has to be submitted to a continuous vibratory type test. . The mercury switches test connected to sensitive detecting equipment and no mal-operations should be recorded. The mercury switches are to be spring mounted within the switch cylinders and protected from possible damage. Alarm and trip circuit mercury switches will make break and carry continuously 2 Amps at 250 Volts A.C or D.C. They will also make and carry for 0.5 sec. 10 Amps at 250 Volts A.C. or D.C.

PRINCIPAL OF OPERATION

The operating mechanism consists of a solid non-metallic cylinder containing the mercury switch, counterbalanced by a smaller solid metal cylinder. Both cylinders are jointed and free to rotate about the same axis, the amount of rotation being controlled by stops. When the relay is empty of oil, the
weight of the switch cylinder predominates and the switch system rests against the bottom stop, the mercury switch being in the closed circuit position. When the relay is full of oil, both cylinders appear to lose weight. Due to the different densities, the switch cylinder appears to lose enough weight to enable the weight of the counterbalance cylinder to predominate and rotate the whole system until it reaches the top stop, with the mercury switch in the open position.

“ALARM” OPERATION

When a slight or incipient fault occurs within the transformer, the gas generated will collect in the top of the relay housing. As gas collects, the oil level will fall and increasing amounts of the alarm switch will appear above the oil level. This results in gradual restoration of the apparent lost weight, until the weight of the switch cylinder predominates. The element rotates as the oil level continues to fall and eventually the alarm switch operates.

TRIP OPERATION

When a serious fault occurs, the generation of the gas is so rapid that an oil surge is set up through the

relay. This oil flow will impinge upon the flap fitted to the trip element causing it to rotate about its axis and so bring the mercury switch to the closed position, which in turn operates the tripping devices.
In the event of serious oil loss from the transformer, both alarm and trip elements operate in turn, in the manner previously described for gas collection. The oil level in the double element relay can be monitored
against a graduated scale on the windows both sides.

SINGLE ELEMENT AND TAP-CHANGER TYPES
Single element type relays are available for 1” bore size, designated 1 SE, which operate indiscriminately for Gas or Oil collection and are suitable for small oil filled transformer, capacitor and potential transformer protection. single element relays can also be used for Tap-Changer type transformers which operate for a surge condition or loss of oil only and allow gas, normally produced during tapchanging operations, to pass freely. The single element relay has only one operating element and operates in a similar manner to that described for the double element types.

Limitations

Only internal below faults below oil level are detected
Mercury switch cannot be set for sensitive operation as it may operate for vibrations and mechanical shocks to the pipes, sitting of birds, etc,.
It is slow in operation compared to electrically operated relays, minimum operating time being 0.1 sec
But it is very good device to detect incipient faults

Chapter-11

11 TRANSFORMER TAP CHANGER

A transformer tap is a connection point along a transformer winding that allows the number of turns to be selected. By this means, a transformer with a variable turns ratio is produced, enabling voltage regulation of the secondary side. Selection of the tap in use is made via a tap changer mechanism

Supply authorities are under obligation to their customers to maintain the supply voltage between certain limits. Tap changers offer variable control to keep the supply voltage within these limits. About 96% of all

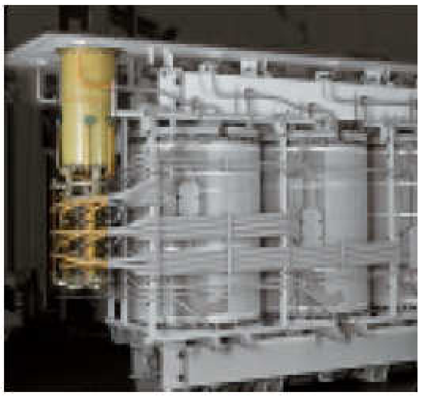


Fig.11.1 In tank OLTC

power transformers today incorporate on load tap changers as a means of voltage regulation.

Tap changers can be on load or off load.

On load tap changers generally consist of a diverter switch and a selector switch operating as a unit to effect transfer current from one voltage tap to the next. It was more than 60 years ago on load tap changers were introduced to power transformers as a means of on load voltage control.

OLTC are generally Oil type means the OLTC is immersed in transformer oil and switching contacts makes and breaks current under oil

Tap changers possess two fundamental features:

(a) Some form of impedance is present to prevent short circuiting of the tapped section, and

(b) A duplicate circuit is provided so that the load current can be carried by one circuit whilst switching is being carried out on the other.

The impedance mentioned above can either be resistive or reactive. The tap changer with a resistive type of impedance uses high speed switching, whereas the reactive type uses slow moving switching. High speed resistor switching is now the most popular method used worldwide, and hence it is the method that is reviewed in this report.

The tapped portion of the winding may be located at one of the following locations, depending upon the type of winding:

(a) At the line end of the winding;

(b) In the middle of the winding;

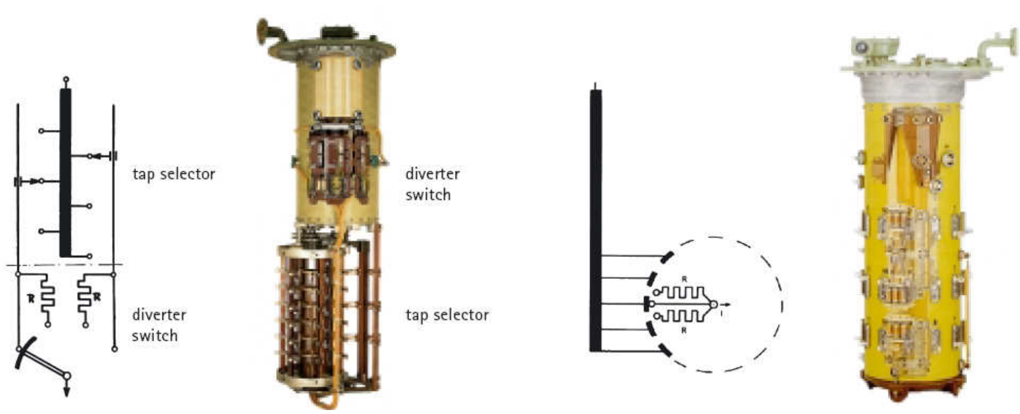
(c) At the star point.

The most common type of arrangements is the last two. This is because they give the least electrical stress between the tap changer and earth; along with subjecting the tapings to less physical and electrical stress from fault currents entering the line terminals.

At lower voltages the tap changer may be located at either the low voltage or high voltage windings.

11.1 Selection of On Load Tap Changers

The selection of a particular OLTC will render optimum technical and economical efficiency if requirements due to operation and testing of all conditions of the associated transformer windings are met. In general, usual safety margins may be neglected as OLTCs designed, tested, selected and operated in accordance with IEEE and IEC standards [4], [5], [12], [13], are most reliable.
To select the appropriate OLTC the following important data of associated transformer windings should be known:
• MVA-rating
• Connection of tap winding (for wye, delta or single-phase connection)
• Rated voltage and regulating range
• Number of service tap positions
• Insulation level to ground
• Lightning impulse and power frequency voltage of the internal insulation
The following OLTC operating data may be derived from this information:
• Rated through-current: Iu
• Rated step voltage: Ui
• Rated step capacity: Pst = Ui x Iu
and the appropriate tap changer can be determined:
• OLTC type
• Number of poles
• Nominal voltage level of OLTC
• Tap selector size/insulation level
• Basic connection diagram
the following characteristics of the tap changer should be checked:
• Breaking capacity
• Overload capability
• Short-circuit current (especially to be checked in case of phase shifting applications)
• Contact life
Fig.11.2 Different switching designs of OLTC's



Switching principle　　Design　　Switching principle　　Design

Tap points are usually made on the high voltage, or low current, side of the winding in order to minimise the current handling requirements of the contacts. To minimise the number of windings and thus reduce the physical size of a transformer, use may be made of a 'reversing' winding, which is a portion of the main winding able to be connected in its opposite direction and thus 'buck' the voltage. Insulation requirements place the tap points at the low voltage end of the winding. This is near the star point in a star connected winding. In delta connected windings, the tappings are usually at the centre of the winding. In an autotransformer, the taps are usually made between the series and common windings, or as a series 'buck-boost' section of the common winding.

The diverter switch and tap selector is the only internal moving parts in a transformer. The diverter switch does the entire on load making and breaking of currents, whereas the tap selector preselects the tap to which the diverter switch will transfer the load current. The tap selector operates off load and therefore needs no maintenance. However experience has shown that in some circumstances inspection of selector switches becomes necessary where contacts become misaligned or contact braids in fact fatigueandbreak.

11.2 Mechanical tap changers

A mechanical tap changer physically makes the new connection before releasing the old, but avoids the high current from the short-circuited turns by temporarily placing a large diverter resistor (sometimes an inductor) in series with the short-circuited turns before breaking the original connection. This technique overcomes the problems with open or short circuit taps. The changeover nevertheless must be made rapidly to avoid overheating of the diverter. Powerful springs are wound up, usually by a low power motor, and then rapidly released to effect the tap changing operation. To avoid arcing at the contacts, the tapchangers is filled with insulating transformer oil. Tapping normally takes place in a separate compartment to the main transformer tank to prevent contamination of its oil.

One possible design of on-load mechanical tap changer is shown to the right. It commences operation at tap position 2, with load supplied directly via the right hand connection. Diverter resistor A is short-circuited; diverter B is unused.
In moving to tap 3, the following sequence occurs:

Switch 3 closes, an off-load operation.
Rotary switch turns, breaking one connection and supplying load current through diverter resistor A.
Rotary switch continues to turn, connecting between contacts A and B. Load now supplied via diverter resistors A and B, winding turns bridged via A and B.
Rotary switch continues to turn, breaking contact with diverter A. Load now supplied via diverter B alone, winding turns no longer bridged. Fig 1. A mechanical on-load tap changer

Rotary switch continues to turn, shorting diverter B. Load now supplied directly via left hand connection. Diverter A is unused.
Switch 2 opens, an off-load operation.
The sequence is then carried out in reverse to return to tap position 2.

Thyristor-assisted tapchangers
Thyristor-assisted tap changers use thyristors to take the on-load current whilst the main contacts change over from one tap to the next. This prevents arcing on

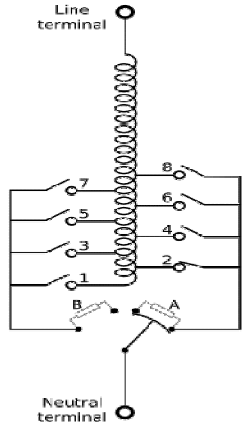
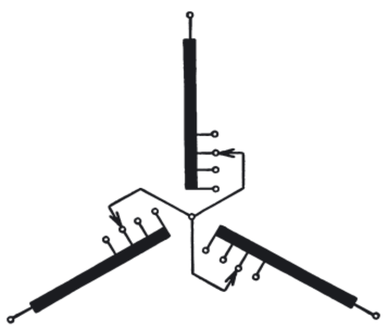


Fig.11.3 OLTC Tap changer

the main contacts and can lead to a longer service life between maintenance activities. The disadvantage is that these tap changers are more complex and require a low voltage power supply for the thyristor circuitry. They also can be more costly

Solid state (thyristor) tap changers
These are a relatively recent development which use thyristors both to switch the load current and to pass the load current in the steady state. Their disadvantage is that all of the non-conducting thyristors connected to the unselected taps still dissipate power due to their leakage current. This power can add up to a few kilowatts which has to be removed as heat and leads to a reduction in the overall efficiency of the transformer. They are therefore only employed on smaller power transformers.

Examples of Commonly Used Winding Schemes



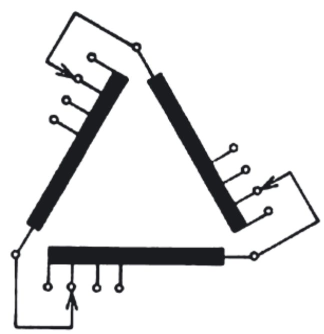


Fig.11.4 OLTC with Neutral end of tap winding   Fig.11.5 Delta connected OLTC 3-pole line-end tap winding

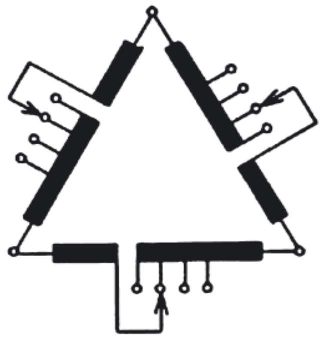
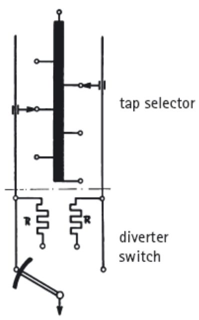


Fig.11.6 Delta connected OLTC 3-pole mid tap winding

The OLTC design that is normally applied to larger powers and higher voltages, comprises a diverter switch (arcing switch) and a tap selector. For lower ratings OLTC designs are used, where the functions of the diverter switch (arcing switch) and the tap selector are combined in a so-called selector switch (arcing tap switch).



With an OLTC comprising a diverter switch (arcing switch) and a tap selector (Fig.5), the tap change operation takes place in two steps (Fig. 6). First the next tap is preselected by the tap selector at no load (Fig. 6 position a-c). Then the diverter switch transfers the load current from the tap in operation to the preselected tap (Fig. 6 position c-g). The OLTC is operated by means of a drive mechanism. The tap selector is operated by a gearing directly from the drive mechanism. At the same time, a spring energy accumulator is tensioned, this operates the diverter switch – after releasing in a very short time – independently of the motion of the drive mechanism.

Fig.11.7 OLTC diverter switch with tap selector

The gearing ensures that this diverter switch operation always takes place after the tap preselection operation has been finished. The switching time of a diverter switch lies between 40 and 60 ms with today's designs. During the diverter switch operation, transition resistors are inserted (Fig. 6 position d-f) which are loaded for 20–30 ms, i. e. the resistors can be designed for short-term loading. The amount of resistor material required is therefore relatively small. The total operation time of an OLTC is between 3 and 10 sec depending on the respective design.

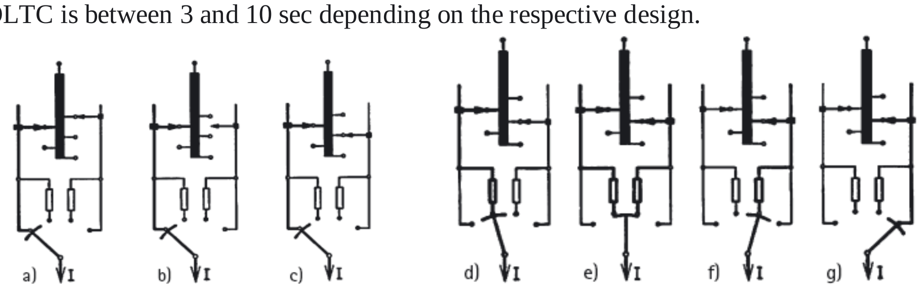


Fig.11.8 switching sequence tap selector   switching sequence diverter switch

Switching sequence of tap selector – diverter switch (arcing switch)

Power transformers equipped with OLTCs are main components of electrical networks. Therefore, the operational reliability of these transformers and their OLTCs is of high importance and has to be kept at a high level during their entire life span.
The principle of a preventive, i. e. periodic maintenance strategy for oil type on-load tap-changers, is based on the time in service or the number of operations
Maintenance and usual check-up on the transformer and include the following
Visual check of the motor drive unit
Protection test of the protective relay of the tap-changer
Monitoring of the tap-changer oil (the dielectric strength is the
decisive criteria)
Regular check of the breather system (Silicagel)

11.3 Tap changer troubleshooting

Load tap changer (LTC) is a mechanical switching device; they are the most expensive and vulnerable accessories on a power transformer and they cause more failures and outages than any other component of a power transformer.
LTC function is to change turns ratio without interrupting the load current. LTC failures are categorized as electrical, mechanical, and thermal. Most of the failures are mechanical at the beginning and developed to electrical faults mainly occurring due to problems on the contacts, transition resistors, and insulation breakdowns.
LTC can be evaluated on-line without affecting its normal operation by using a combination of acoustic emission and vibration techniques (AE/VA).
Acoustic Emission assessment is based on the fact that no acoustic activity is expected from inside the LTC compartment if the tap changer is not being operated and if it is in good condition
Vibration technique consists in obtaining the signature of one operation of the tap changer and performs the comparison of its characteristics (time, amplitude, energy, etc.) with another signature obtained some time in the future or with a sister unit having the same operation.
When using a combination of both techniques, the evaluation of the condition of the tap changer when it is not being operated is performed by using acoustic emission whereas the evaluation during an operation is made by the vibration technique.

New developments :

A new type of vacuum switching technology is being developed to be – used in OLTCs – is going to be the “state of the art” design at
present time and foreseeable future.
transformers that do not use conventional mineral oil as insulating or switching medium,such as gas-immersed transformers, drytype transformers, and transformers with alternative insulating fluids meet these requirements the conventional tapchangers are not suitable, because the use of mineral oil as switching medium is – for the reasons mentioned above – not desirable and would moreover require technically complex and expensive overall solutions.
vacuum type OLTC’s superiority to competing switching technologies in the range of low and medium power is based on

• The vacuum interrupter is a hermetically sealed system
There is no interaction with the surrounding medium, despite the arc
The switching characteristics do not depend on the surrounding medium
• The arc (drop) voltage in vacuum is considerably lower than in oil or SF6
Low energy consumption
Reduced contact wear
• Elimination of the insulating medium as the arc quenching agent
Elimination of by-products e. g. carbon when using transformer oil
On-line filter becomes unnecessary
Easy disposal
• No ageing of the quenching medium, Constant or even improving switching characteristics throughout the entire life of the vacuum interrupters (getter effect)
• No interaction/oxidation during switching
High rate of re-condensation of metal vapor on contacts extends contact life
Constantly low contact resistance
• Extraordinary fast dielectric recovery of up to 10 kV/µs
Ensures short arcing times (maximum one half-cycle) even in case of large phase angles between current and voltage or high voltage steepness dU/dt after the current zero (converter transformers).

Since the early seventies vacuum interrupters that fulfilled the characteristics required by reactor type OLTCs have been developed.
These OLTCs, which in general are external compartment type designs, did not dictate any special requirements in regards to the physical size of the interrupter. Not so with resistor type OLTCs, which in general have

Fig.11.9 selector switch contact system with roller contacts

a very compact design. Today, after more than three decades of development, vacuum interrupters have reached an advanced technical performance level. The use of modern clean room and furnace soldering technologies during the production process, and new designs of contact systems and material are some of the milestones for this reliable product. This has made possible the design of considerably smaller vacuum interrupters, opening the door for its application in resistor type OLTCs with overall dimensions equivalent to those of conventional resistor type OLTC designs

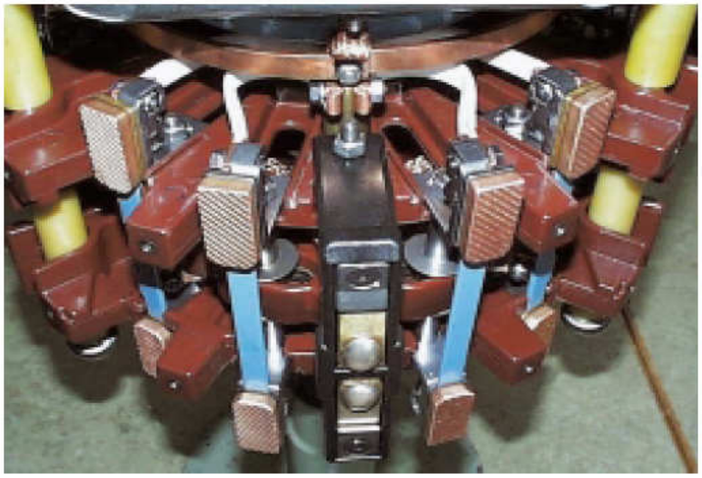


Fig.11.10 diverter switch contact system
OLTCs with tungsten-copper arcing contact system for oil filled transformers (different scales)

Fig.11.12 Vacuum interrupter designed for different OLTC diverter switches

Chapter-12

12 TRANSFORMER TESTING

Power transformers are the most expensive single elements of HV transmission systems which are designed and required to remain in operation for a number of decades. Therefore, it is essential to check the transformer for any defects and deviations from the rated values and must be capable of withstanding different types of electrical faults as well as mechanical and atmospheric adverse conditions.
To confirm this the Power transformer is to be tested thoroughly at different stages of manufacturing, after transport and before commissioning.

12.1 Types of Tests

The following test are done

- Type tests
- Routine tests
- Special tests
- Commissioning tests.

Type test : is performed on a single transformer of the specific type and intended to confirm the design soundness of the transformer. Type test relates to a first or one manufactured to a given specification and it is presumed that all the transformers build to this specification complies with type test as the design and method of manufacture is identical.
Routine test are conducted by the manufacturer on all transformers before dispatch and special tests are conducted if specified in the purchase document, these tests are to be made in the presence of the purchaser's engineer.
Commissioning tests are done at site with all the associated equipment and switchgear in place, before charging the transformer.

Table 12.1

Type Tests

Items	Objective	Method	Capacity / Equipment
1. Temperature-rise test	To measure temperature rise of oil and winding of transformer	1. Actual loading 2. Simulated loading 2.1 short circuit method 2.2 The loading back method	Measures temperature rise of oil and winding of transformer. /PT ,CT, Volt-Amp-Watt meter
2.Dielectric type test (Lightning and switching Impulse test, BIL)	To certify that the transformer has been designed and constructed to withstand the specified (BIL)insulation levels	Marx's multiplier circuit	Measures dielectric of the transformers (BIL) / Impulse Generator s E Max. Voltage 1400 kV 70 kJ

Table 12.2

Special Tests

Items	Objective	Method	Capacity
1. Dielectric special test BIL FW&CW	To certify that the transformer has been designed and constructed to withstand the specified insulation levels	Marx's multiplier circuit	1. Impulse Generator E Max. Voltage 1400 kV 2. Chopping Gap 1200 kV
2. Determination of capacitance winding-to-earth, and between windings	To measure capacitance of transformer	Bridge method	Measures capacitance of the transformer. /Bridge capacitance meter
3. Measurement Zero-sequence impedance on three phase transformer	To measure Zero phase sequence impedance	Winding shall be excited at rated frequency between the neutral and three line terminal connected together	Measures Zero phase sequence impedance of the transformer. /PT ,CT, Volt-Amp-Watt meter
4. Determination of sound level	To measure sound level originating from active part of transformer which is transmitted, either through the dielectric fluid or the structure supports, to the outer shell or to other solid surfaces from which it is radiated as airborne sound	1. Measuring continuous sound pressure levels, In term of either A-weight 2. Rating transformer sound emissions 3. Report the result in a standard manner	Measures sound from active part of transformer. /sound level meter
5. Measurement of the dissipation factor (tan d) of the insulation system capacitance	To determine ratio of the power dissipated in the insulation in watts to the product of the effective voltage and current in volt-amperes when test under a sinusoidal voltage	Bridge circuit	Measures the dissipation factor (tan d) of the insulation system capacitance . /Bridge capacitance meter
6. Determination of partial discharge on transformer	To measure the radio-influence voltage (RIV) generated by any internal partial discharge	Measures partial discharge in terms of RIV and will be measured at the line terminal of the winding under test	Measures partial discharge level of transformer. /PD Detector and PD analyzer,

Table 12.3

Routine Tests			
Items	**Objective**	**Method**	**Capacity / Equipment**
1. Voltage ratio test	To measure voltage ratio between windings	1.Voltmeter method 2.Comparision method	transformers have ratio and phase deviation not

	of transformer	3. Ratio bridge method	more than +- 0.5%
2. Polarity	To determine polarity (sub. or additive)	1. Inductive kick 2. Alternating voltage 3. Comparison 4. Ratio bridge	Measures polarity of transformer. / Volt-Amp-Watt meter
3. Phase relation test	To determine angular displacement and relative phase sequence	1. Phasor diagram 2.ratio bridge 3. excited voltage	Measures angular displacement and phase sequence (vector group) of the transformer
4. Resistance measurements	To measure resistance of transformer winding	1. Bridge method 2. Voltmeter-ammeter method	Measures resistance of transformer winding /Volt-Amp-Watt meter
5. No-load loss test	To measure no-load loss at specified excitation voltage and specified frequency	1. Average-voltage voltmeter method	Measures core loss of transformer/ PT ,CT, Volt-Amp-Watt meter
6. Exciting current test	To measure current that maintain the magnetic flux excitation in the core of the transformer	1. Average-voltage voltmeter method	Measures exciting current of the transformer / PT ,CT, Volt-Amp-Watt meter
7.Load loss and impedance test	To measure losses occurring at rated load , including I2R loss and stray loss and measured voltage required to circulate rated current through one winding when the other winding is short-circuited	Wattmeter-voltmeter-ammeter method	Measures load loss of the transformer / PT,CT, Volt-Amp-Watt meter
8.Induce potential test	To check insulation turn to turn and between layers of the winding	Applied greater than rated volts per turn to the transformer , the frequency of the impressed voltage must be high enough to limit the flux density in the core	1. Generator 500 kW Max. frequency 500 Hz 2. Generator 250 kW frequency 200 Hz 3. Testing Transformer 4000 kVA 1.5/6.9/50 kV

Table 12.3 contd.

Routine Tests

Items	Objective	Method	Capacity / Equipment
9. Applied potential test	To test the transformers ability to withstand application of voltage associated with the specified	Applied potential at power frequency to specified value and held for the time specified.	1. HV Testing Transformer (3 x 75 kVA) 400V/0-250 kV 2. Reactor

	insulation level (insulation between winding -winding and winding - ground)		
10. Oil test	To determine oil dielectric strength	Oil Tester (applied high voltage until gap in oil breakdown and measure this voltage)	Measures dielectric strength of transformer oil. / Oil Tester
11. Insulation resistance test	To determine the insulation resistance from individual windings to ground or between individual windings	Mega ohmmeter (applied dc voltage)	Measures insulation resistance of the transformer. / Mega ohmmeter
12. Leakage test	Check leakage of tank	Pressurize tank by applying dry nitrogen. if after 6 hours no pressure drop is registered the transformer tank is leakage free	Check for tank leakage

12.2 Type Tests

1. Temperature-rise test :

Transformers are tested under a loading condition that will give losses as near as possible to those obtained when the tranformer is operating at its nameplate rating. Transformers are tested on the tap connection giving the highest winding temperature rise which is considered to be reached when the temperature rise does not vary more than 2ºC during consecutive 3 hour periods. Surface temperatures are measured by thermocouples. Average winding temperature and average winding temperature rise are measured by the hot-resistance method. Ambient temperature shall be taken as that of the surrounding air, which should be not less than 10°C or more than 40°C.

TEST PROCEDURE FOR TEMPERATURE RISE MEASUREMENTS

Keep transformers to be tested in room temperature of 25 0C ±3 0C for 24 hours before testing for temperature rise.

2. Using the Ohmmeter , measure the secondary coil resistance of the transformer with the primary coil open circuited.
3. Record the room temperature, T1, in degrees C and the coil resistance, R1.
4. Arrange the apparatus as shown in Figure 1 with commercial power off.
5. Connect the transformers to the 6.6 amp series circuit outputs A through E. Disconnect the series circuit shorting switches for the outputs that are loaded with transformers and make certain that the outputs which have no transformers connected to them are shorted with the shorting switches.
6. Note the volt-ampere capacity of each transformer being tested for temperature rise and connect sufficient load to each transformer approximately equal to its volt-ampere capacity.
7. Turn on the power to the constant current transformer. Adjust the lamp load so that the product of the transformer minutes or more.
8. Leave transformers on in the overload condition for 4 hours. After 4 hours, reduce the load to equal the volt-ampere capacity of the transformer. Wait 2 more hours.

9. Turn off the commercial power. Disconnect both primary and secondary wires of the transformers. Measure the secondary coil resistance as in step D-2.
10. Record the coil resistance, R2. 11. Connect the transformer back in the circuit. Turn on the commercial power to the constant current transformer. Wait 15 minutes or more.
12. Repeat steps 9 through 11 at least 2 more times until no further change is observed in the secondary coil resistance.
13. Repeat steps 9 through 12 for each of the remaining transformers.
14. The temperature rise shall be determined after the temperature of the transformer has become constant. The temperature shall be considered constant when 3 successive readings of the resistance taken at inimum intervals of 15 minutes indicate no change.
15. The resistance measurement of the transformer shall be completed within 4 minutes after shut-down to get an accurate reading.
16. The temperature rise shall be calculated

$T\,\Delta = [\,(R_2 — R_1) / R_1\,] \times (234.5 + T_1)$

Where:

$T\,\Delta$ = Temperature rise.
R_1 = Cold resistance of transformer coil.
R_2 = Hot resistance of transformer
coil.
T_1 = Room temperature in degrees C.
17. Turn off the commercial power. Close the series circuit shorting switches before removing the transformer.

2. Dielectric type test (Lightning and switching Impulse test, BIL)
Surge or impulse tests

These tests are carried out in order to investigate the influence of surges in transmission lines, breakdown of insulators and of the end turns of transformer connections to line. In impulse testing, to represent surges
generated due to lightning, the IEC Standard impulse wave of 1.2 /50 µs (1.2 times BIL for 50 µs) wave is generally used. By the use of spark gaps, conditions occurring on the flash over to line are simulated. The total duration of a single lightning strike os about 100 s, although the total duration of the lightning stroke may be a few seconds.
Overvoltages of much higher duration also arise due to line faults, switching operations etc, for which impulse waves such as 100/5000 micro sec duration may be used.
In surge tests it is required to apply to the circuit or apparatus under test, a high direct voltage whose value rises from zero to maximum in a very short time and dies away again comparatively slowly .
Methods of generating such voltages have already been discussed earlier.
While impulse and high frequency tests are carried out by manufacturers, in order to ensure that their finished products will give satisfactory performance in service, the most general tests upon insulating materials are

Flash-over Tests

Porcelain insulators are designed so that spark over occurs at a lower voltage than puncture, thus safeguarding
the insulator, in service against destruction in the case of line disturbances. Flash-over tests are very importance
in this case .

The flash-over is due to a breakdown of air at the insulator surface, and is independent of the material of the insulator. As the flash-over under wet conditions and dry conditions differ , tests such as the one minute dry flash-over test and the one minute wet flash-over test are performance.
(i) 50 percent dry impulse flash-over test, using an impulse generator delivering a positive 1/50 μs impulse wave. The voltage shall be increased to the 50 percent impulse flash-over voltage (the voltage at which approximately half of the impulses applied cause flash-over of the insulator)
(ii) Dry flash-over and dry one-minute test In this the test voltage (given in the B.S.S.) is applied . The voltage is raised to this value in approximately 10 seconds and shall be maintained for one minute. The voltage shall then be increased gradually until flash- over occurs .
(iii) Wet flash-over and one minute rain test
In this the insulator is sprayed throughout the test with artificial rain drawn from source of supply at a temperature within 10 degrees of centigrade of the ambient temperature in the neighborhood of the insulator.
The resistivity of the water is to be between 9,000 and 11,000 ohm cm.
In the case of the testing of insulating materials , it is not the voltage which produces spark-over breakdown
which is important , but rather the voltage for puncture of a given thickness (ie. dielectric strength) . The
measurements made on insulating materials are usually , therefore , those of dielectric strength and of dielectric loss and power factor , the latter been intimately connected with the dielectric strength of the material.
It is found that the dielectric strength of a given material depends , apart from chemical and physical properties of the material itself, upon many factors including,

1. thickness of the sample tested
2. shape of the sample
3. previous electrical and thermal treatment of the sample
4. shape , size , material and arrangement of the electrodes
5. nature of the contact which the electrodes make with the sample
6. waveform and frequency of the applied voltage (if alternating)
7. rate of application of the testing voltage and the time during which it is maintained at a constant value .
8. temperature and humidity when the test is carried out
9. moisture content of the sample.

Impulse Testing

These are done as tests on sample of apparatus. The impulse test level is determined by the operating level (4 to 5 times the normal operating value) Apply on to the sample a certain number (say 10) positive impulse and 10 negative impulses of this particular value. They should withstand this voltage without any destruction.
To test the ultimate impulse strength, apply increasing amounts of impulse voltage until destruction occurs;
during the tests it is necessary to see whether there is any damage. The damage may not be immediately visible, so we have it on a high frequency (single sweep and high speed) oscilloscope.
In the event of complete damage, breakdown of the insulator due to the application of the impulse voltage will be indicated as in (i). If the insulator has suffered only a minor damage the wave form

would show no distortion , but would show as in (ii). If there is no damage caused due to the impulse, the waveform will be complete and undistorted as in (iii).
In testing high voltage insulators whose actual breakdown is in air (i.e flashover takes place before breakdown of insulator) the porcelain itself can be tested by immersing the whole insulator in liquid of high permeability so that there would be no outside flashover, and actual breakdown of the insulator would occur.

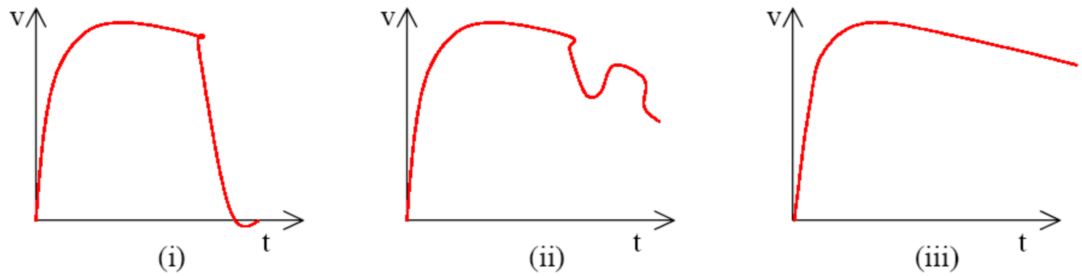


Fig.12.1 Observed impulse waveforms

In specifying the flashover characteristic in air we give the 50% flashover characteristic.
This is done as flashover occur at the same voltage on each application of the impulse . We apply different values of test voltages (impulse) and the voltage at which there is 50% probability of breakdown is taken as 50% flashover voltage.

The impulse flashover voltage also depends on the time lag of the applied impulse before flashover time lag of the applied impulse before flashover occurs. Thus we have also got to determine the time lag characteristics for breakdown.

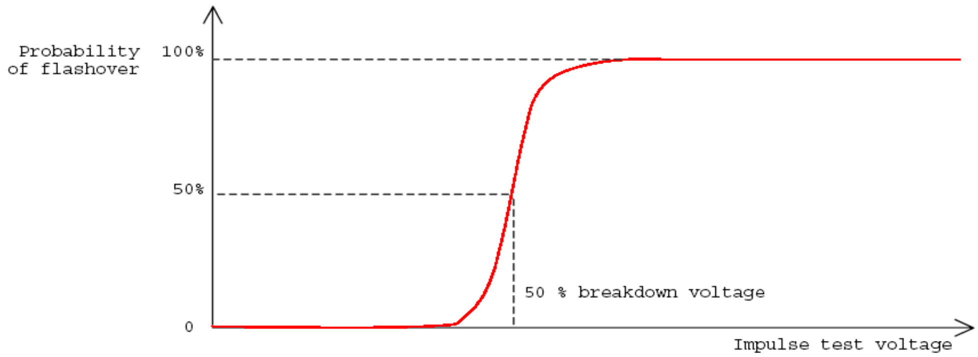


Fig.12.2 Probability of flashover

If the voltage remains above a critical value long enough, flashover occurs.
The time lag before flashover occurs depends on the statistical time lag and on the formation time lag.

Depending on the volume of space between the gap, and also depending on the nature of shielding, a certain time will be taken for enough free electrons to be set free.This is the statistical time lag.
Once the electrons appear, depending on the voltage applied, they multiply and ionise the space. once the space becomes conducting, flashover occurs. This is formation time lag.
To determine the time lag characteristic of a device, we can use the impulse generator to generate impulses of gradually increasing amplitude and determine the time of breakdown. At each value, the test must be repeated a number of times so as to obtain consistent values.

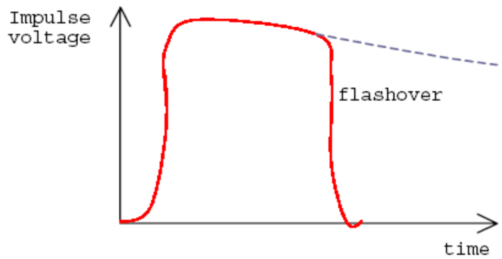


Fig.12.3 Chopped impulse waveform

This type of characteristic is important in designing insulators.If a rod gap is to protect a transformer. Then the breakdown voltage characteristic of the rod gap must be less than that of the transformer so as to protect it. If the characteristic cross, protection will be offered only in the region where the rod gap characteristic is lower than that of the transformer.

Table 12.4

System Voltage	I.E.C. Impulse Withstand Voltage
11 kV	75 kV
33 kV	170 kV
66 kV	325 kV
132 kV	550 kV
275 kV	1050 kV

Determination of capacitance winding-to-earth, and between windings

Consider the entering of an impulse voltage on the terminating transformer, as shown in figure 9.11.

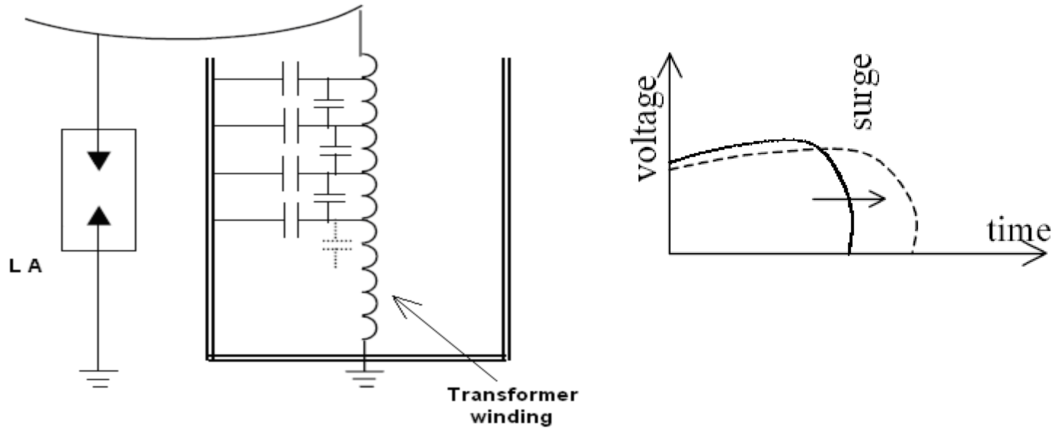


Fig.12.4 Surge propagation in transformer winding

Due to the presence of the interwinding capacitance and the capacitances to earth of the transformer windings, the upper elements of the transformer windings tend to be more heavily stressed than the lower portions. Due to the velocity of propagation of the impulse voltage would not be evenly distributed in the winding. Due to sharp rise of the voltage of the surge. there is a large difference of voltage caused in the winding as the wave front travels up the winding. Thus there would be an overvoltage across adjacent windings. Depending on the termination, there will be reflections at the far end of the winding. If the termination is a short circuit, at the lowest point the voltage wave whose amplitude is same as the original wave but of opposite polarity is reflected. For a line which is open circuited, the reflected wave would be of the same magnitude and of the same sign.
Arising out of the reflections at the far end , there would be some coils heavily stressed. The position of the
heavily stressed coils depending on the velocity of propagation. If flashover occurs at the gap (lightning arrestor) the voltage of the impulse suddenly drops to zero when flashover occurs. This can be represented by a full wave, and a negative wave starting from the time flashover occurs. The chopped wave, though it reduces the voltage of the surge to zero, will have a severe effect of the winding due to sharp drop in the voltage. Thus it is always necessary to subject the transformer during tests to chopped wave conditions. Generally the method is to apply full-waves and see whether damage has occurred and then to apply the chopped waves and to see whether damage has occurred and then to apply the chopped waves and to see whether damage has occurred.

Measurement Zero-sequence impedance on three phase transformer

Purpose of the measurement

The zero-sequence impedance is usually measured for star or zig-zag connected windings of the transformer. The measurement is carried out by supplying a current of rated frequency between the parallel connected phase terminal. The zero-sequence impedance per phase is three times the impedance measured in this way. The zero-sequence impedance is needed for earth-fault protection and earth-fault current calculations.

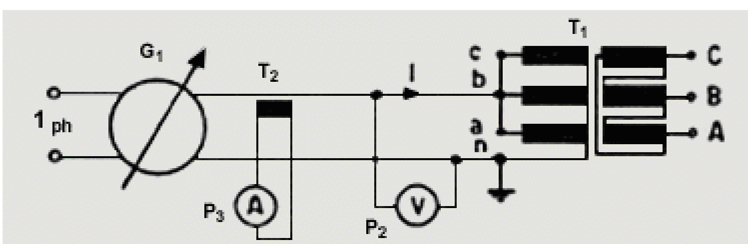


Fig.12.5 Circuit for zero-sequence impedance measurement

MEASURING CIRCUIT AND PERFORMANCE OF MEASUREMENT

G1 supply regulator, **T1** transformer to be tested, **T2** current transformer, **P2** voltmeter, **P3** ammeter, **I** test current.

The zero-sequence impedance is dependent on the current flowing through the winding. It is measured as a function of test current, and when necessary the final result is obtained by extrapolation.

Measuring Impedance
The impedance is measured by means of a short circuit test. With one winding shorted, a voltage at the rated frequency is applied to the other winding sufficient to circulate full load current - see below:

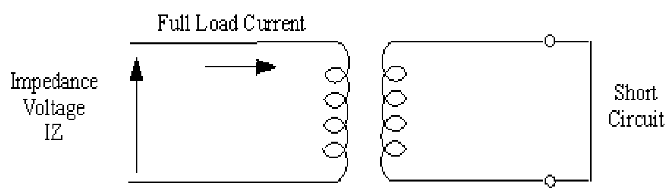


Fig.12.6 Measuring impedance

The percentage impedance can then be calculated as follows:

$$Z\% = \frac{\text{Impedance Voltage}}{\text{Rated Voltage}} \times 100$$

Sequence Impedance (Z_1 Z_2 Z_0)
The calculation above deals with a balanced 3-phase fault. Non-symmetrical faults (phase-earth, phase-phase etc) lead to more complex calculations requiring the application symmetrical component theory. This in turn involves the use of positive, negative and zero sequence impedances (Z_1, Z_2 and Z_0 respectively).

As with all passive plant, the positive and negative sequence impedances (Z_1 and Z_2) of a transformer are identical.

However, the zero sequence impedance is dependent upon the path available for the flow of zero sequence current and the balancing ampere turns available within the transformer. Generally, zero sequence current requires a delta winding, or a star connection with the star point earthed. Any impedance in the connection between the star point and earth increases the overall zero sequence impedance. This has the effect of reducing the zero sequence current and is a feature that is frequently put to practical use in a distribution network to control the magnitude of current that will flow under earth fault conditions.

Transformer Sound/Noise

A Humming is an inherent characteristic of transformers due to the vibration caused by alternating flux in the magnetic core. Sound levels will vary according to transformers due to the vibration caused by alternating flux in the magnetic core. Sound levels will vary according to transformer size.Attention to installation methods can help reduce any objectionable noise. When possible ,locate the transformer in an area where the ambient sound will be equal or greater than the noise of the transformer sound level. Avoid locating units in corners. Make connections with flexible conduits and couplings to prevent transmitting vibration to other equipment. Larger units should be installed on flexible mountings to isolate the transformer from the building structure.

Sound Level in Decibels

Table 12.5

KVA	**Decibels**
150 Degrees Celcius Rise K-1	Average
0-9	40
Oct-50	45
51-150	850
151-300	55
301-500	60
501-700	62
701-1000	64

Measurement of Tan Delta and Capacitance of Bushings of Transformers and Winding paper insulation

The above measurement gives an indication of the quality and soundness of the insulation in the bushings. For obtaining accurate results of tan delta and capacitance without removing the bushings from the transformers a suitable test set capable of taking measurement by ungrounded specimen test method shall be employed. This utilizes the test tap of the bushings and a tan delta/capacitance test set. Both tan delta and capacitance can be measured using the same set-up. Portable capacitance and tan delta bridge from any reputed manufacturer could be used for this test. Portable test set include measuring bridge such as SCHERING Bridge or transformer ratio arm bridge, power supply and standard capacitor in one enclosure.

Proper safety instructions as per utility practice and necessary isolation required is to be done prior to commencement of this test. Following precautions may be observed during this test:

1. Measurement may be made on low voltages preferably below 10 kV. It is preferred to have the bridge frequency different but close to operating power frequency, so that stray power frequency currents do not interfere with the operation of the instrument.
2. Measurement shall be made at similar conditions as that of the previous measurement. In the event of measurement being made a varying temperature correction factor have to be applied wherever applicable.

3. Porcelain of the bushing should be clean and dry. Remove any dirt or oil with clean dry cloth.
4. Test shall not be conducted when there is a condensation on the porcelain. Relative humidity in excess of 75% is preferred.
5. Connection to the overhead bus at the bushing need to be removed, only if the bus line affect the readings considerably.
6. Terminals of the bushings of each windings to be shorted together using bare braided copper jumper. Transformer windings not being tested shall be grounded.

Evolution of Test Results

A large percentage of electrical equipment failure has been reported due to deteriorated condition of the insulation. A large number of these failures can be anticipated in advance by regular application of this test. Changes in the normal capacitance of insulation indicates abnormal conditions such as presence of moisture, layer short circuits or open circuit in the capacitance network.

The interpretation of the dielectric measurement are based on observing the difference:

1. Between measurements on the same unit after successive intervals of time.
2. Between measurements on similar part of a unit, tested under the same conditions around the same time e.g. several identical transformers or one winding of a three-phase transformer tested separately.
3. Between measurements made at different test voltages on one part of a unit; an increase in slope (tip up) of DF vs Voltage curve at a given voltage in an indication of ionization commencing at that voltage.

An increase of DF accompanied by a marked increase in capacitance usually indicates presence of excessive moisture in the insulation. An increase of DF alone may be caused to thermal deterioration or by contamination other than water. Surface of the insulator petticoats must be cleaned otherwise any leakage over terminal surfaces may add to the losses of the insulation itself and may if excessive, give a false indication of its condition.

Maximum value of tan delta of class insulation i.e. paper insulation, oil impregnated is 0.007. Rate of change of tan delta and capacitance is very important. Capacitance value can be within + 10%, - 5% in capacitance value.

The temperature correction factor to be applied for temperature other than 20° C is given in the following table 12.6 which is based on IEEE 57 standard.

Table 12.6

Ambient temperature in °C	Temperature correction factor
10	0.8
15	0.9
20	1
25	1.12

30	1.25
35	1.4
40	1.55
45	1.75
50	1.95
55	2.08

Partial Discharge Detection in Transformers

Detecting partial discharge in the insulation and windings of power and instrument transformers is a well-documented use of **acoustic emission** monitoring. Discharges are due to electric arcing, which vaporizes the dielectric fluid in the discharge path, creating a bubble cavitation effect. These sudden bursts of acoustic energy are transmitted by the fluid to the external wall, where an acoustic emission sensor can sensitively pick them up. There are special instruments for this application, combining thresholded event and counts measurement, along with modulated audio output. The ideal frequency range has been determined from previous studies to be 100-200 kHz.
Since the induced acoustic signal will transmit a number of feet in the wall before becoming completely attenuated, the location of the source must be determined by probing at several locations in a search pattern until the strongest signal is obtained (highest count rate). A regular maintenance program might include recording the readings at standardized locations on the exterior shell of the transformer.

Discharges typically take place in a regular pattern associated with the 50-cycle AC waveform as shown in the oscilloscope image below.

Fig.12.7 Core noise associated with the transformer power cycle—no discharges.

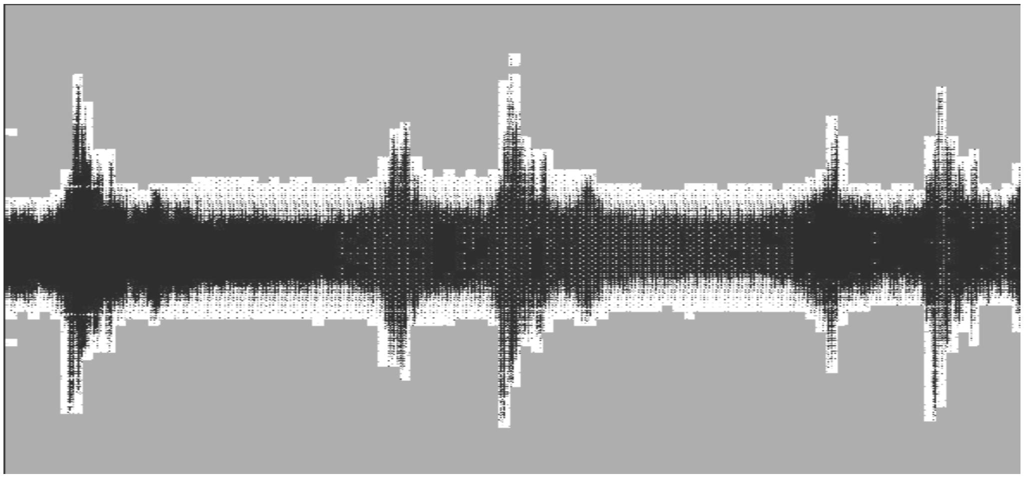


Fig.12.8 Partial discharge burst-like emissions evident on power cycle at regular intervals. denotes Transformer needs to be checked thoroughly

The AE (Acoustic Threshold)is set above the core noise level, so only the burst type emission activity is counted (events and counts). In the RMS mode, the peak –to-average RMS ratio should also show an increase when such activity is detected.

12.3 Routine Tests

Measurement of voltage ratio and check of phase displacement

These measurements are made to verify the voltage ratio of the windings, their interconnections and phase displacement, i.e. vector group. For purposes of measurement, the transformer is exited by a low voltage (some tens of volts) and, using a null method, comparison is made with an accurate, adjustable voltage ratio standard.

The observed ratios are accepted if they are within the tolerances of the relevant standard.
All standards which are adjusted to IEC permit a tolerance of 0.5 % of the ordered ratio on the principal tapping or a percentage of deviation which equals 1/10 of the measured impedance on the principal tapping.
The tolerance for other tappings is to be agreed, but not less than the lowest of the values above.

The turns ratio of a transformer is defined as the number of turns on its secondary divided by the number of turns on its primary.
The voltage ratio of an ideal transformer is directly related to the turns ratio:

$$\frac{Vs}{Vp} = \frac{Ns}{Np}$$

The current ratio of an ideal transformer is inversely related to the turns ratio:

$$\frac{Ip}{Is} = \frac{Ns}{Np}$$

Where Vs = secondary voltage, Is = secondary current, Vp = primary voltage, Ip = primary current, Ns = number of turns in the secondary winding and Np = number of turns in the primary winding.

TR (turns ratio). This test energizes any chosen winding at a specified voltage and measures the induced voltage on any other winding. The results are then presented as a ratio (e.g. 2:1, 5:1, etc.) Voltech AT testers do this by dividing one voltage by the other while compensating for winding resistance. Phase is also measured: 'in-phase' (positive polarity) and 'antiphase' (negative polarity).

VOC (voltage open circuit). This test applies a voltage to the primary winding, reads the voltage induced in the secondary winding and presents the results as a secondary voltage using aMegger of 500V, the test is suitable for testing low-frequency power transformers. Phase is also measured: 'in-phase'
(positive polarity) and 'anti-phase' (negative polarity).

Transformer Oil Quality Tests

following Oil Quality Tests are performed to check is the conditions of transformer oils. These tests are carried out by qualified chemists at accredited laboratories.
Dielectric Breakdown Voltage Test (IEC 60156)
This test determines if the transformer oil has adequate insulating strength. Low insulating strength of oil can lead to transformer failure.
Water Content Test (IEC 60814)
This test determines the water content in the insulating oil based on the Karl Fisher method. The presence of water can adversely affect the dielectric strengths of the insulating oil.

Acidity Test (IEC 60296)
This test measures the acids content of the oil. The build-up of acidic compounds cause the formation of sludge in the transformer. Sludge has an adverse effect on the cooling ability of the insulating oil that can lead to transformer overheating.

Corrosive Sulphur Test (ISO 5662)
This test detects the presence of corrosive sulphur in the insulating oil. Sulphur can cause corrosion to the winding insulation and conductor of transformer.

From the quantity and type of each gas detected, engineers can determine if the transformer has partial discharge, thermal fault or arcing problem.

Test for dielectric strength (BDV)

Using a BDV test kit, adjust the electrodes (12.5 mm dia) slot that a gap of 2.5 mm is between them. Carry out six tests on the oil, stirring the oil between each breakdown and allowing it to settle. Take the average result of the six figure and this should be used for acceptance criteria (i.e. 60 kV)
Tests for moisture content (ppm)

Using an automatic moisture content test set and a suitable syringe that has been flushed, inject a sample of the oil into the test set. Depending upon the make of the test set the moisture figure may be indicated by mg H_2O. if this is the case the figure may be divided by weight of the sample injected in grams. This will give in parts per million (ppm). Typically the moisture content should be less than 15 ppm for transformers in service.

The recommended values of insulating oil for new / unused oil before filling in the equipment (as per IS: 335/1983) and after filling in the equipment (as per IS:1866/1983) are given below in Table 12.7 & 12.8

Table 12.7

S. No.	Chracteristics / Property	Standard value
1	Appearance	Clear & transparent, free from suspended matter or sediments
2	Colour	
3	Density at 29.5° C, Max.	0.89 g/cm^3
4	Kinematic Viscosity at 27° C, Max	27 cst
	Kinematic Viscosity at 40° C, Max	< 9 cst
5	Interfacial tension (IFT) 29.5° C, Min.	0.04 N/m
6	Flash point, Pensky Martin (Closed), Min.	140° C
7	Pour point, Max.	- 6° C
8	Acitity, Neutralisation value	
a.	Total acidity, Max.	0.03 mg KOH / g
b.	Inorganic acidity / Alkalinity	NIL
S. No.	**Chracteristics / Property**	**Standard value**
9	Corrosive Sulphur	Non-corrosive
10	**Di-electric strength (Breakdown Voltage), Min.** gap of 2.5 mm	
a.	New unfiltered oil	30 kV, rms
b.	After filteration	60 kV, rms
11	Dielectric dissipation factor (Tan δ) DDF at 90° C, Max.	0.002
12	Specific resistance (resistivity)	
a.	At 90° C, Min.	35*1012 Ω -cm
b.	AT 27° C, Min.	1500*1012 Ω -cm

13	Oxidation Stability	
a.	Neutralisation value after oxidation, Max.	0.40 mg KOH / gm
b.	Total sludge after oxidation, Max.	0.10% by weight
14	Ageing characteristics after accelerated ageing (Open Breaker method with copper ctalyst)	
a.	Specific Resistance (resistivity)	
i.	At 27° C, Min.	2.5*1012 Ω -cm
ii.	At 90° C, Min.	0.2*1012 Ω -cm
b.	DDF at 90° C, Max.	0.2
c.	Total Acidity, Max.	0.05
d.	Total sludge value, Max. % by weight	0.05

S.No.	Chracteristics / Property	Standard value
15	Presence of oxidation inhibitor	Max. 0.05% treated as absence of oxidative inhibitor
16	Water content	
a.	New unfiltered oil	50 ppm
b.	After filtration	15 ppm
17	PCB content	<2 ppm
18	SK value	4 to 8%

Table 12.8

S.No.	Chracteristics / Property	Standard value
1	Appearance	Clear & transparent free from suspended matter or sediments

2	Interfacial tension (IFT) 29.5° C, Min.	0.018 N/M, Min.
3	Flash point, Pensky Martin (closed), Min.	125° C, Min
4	Total acidity, Max.	0.5 mg KOH/g
5	Di-electric strength (breakdown voltage) BDV Min. gap of 2.5 mm	Below 72.5 kV – 50 kV Min. 72.5 to including 145 kV – 40 kV, Min. 145 kV & above – 30 kV Min.
6	Dielectric dissipation factor (Tan d) DDF at 90° C, Max.	Below 145 kV – 0.2 Max. 145 kV & above – 30 kV Min.
7	Specific resistance (resistivity) – At 90° C, Min.	0.1*1012 W -cm
8	Water content, Max.	Below 145 kV – 25 ppm Max. 145 kV & above – 35 ppm Max.
9	Dissolved gas analysis (DGA)	145 kV & above – as per IS 10593 latest rev.

Prior to energisation of transformer, the oil sample shall be tested for properties and acceptance norms as given in Table 12.9.

Table 12.9

S.No.	Particulars of test	Acceptable value
1.	BDV (kV rms)	60 kV (Min.)
2.	Moisture content	15 ppm (Max.)
3.	Tan delta at 90° C	0.05 (Max.)
4.	Resistivity at 90° C	1*10 : -cm (Min.)
5.	Interfacial tension	0.03 N/m (Min.

Measurement of Insulation Resistance of Transformer

The measurement of insulation resistance is carried out to check the healthiness of the transformer insulation. This test is the simplest and is being widely used by the electrical utilities. This test indicates the condition of the insulation i.e. degree of dryness of paper insulation, presence of any foreign containments in oil and also any serious defects in the transformer. The measurement of insulation resistance is done by means of megger of 2.5 kV for transformer windings with voltage rating of 11 kV and above and 5 kV for EHV transformers.
All safety instructions have to be followed as per the utility practice before carrying out this test. It has also to ensured that high voltage and low voltage windings are isolated along with the concerned

isolaters. In case transformer is having a tertiary windings, ensure the isolation are the same prior to commencement of the test. Also the jumpers and lighting arrestors connected to the transformer have to be disconnected prior to start of testing after issue of PTW/SFT.

Following precautions may be taken while conducting the above test.

1. Bushing porcelain may be cleaned by wiping with a piece of the dry cloth.
2. When using a megger, observe the usual accident preventive rules.
3. As the windings possess a substantial capacitance, the current carrying cords should only be touched after the electric charge have been removed from them.
4. Connecting wires from the bushing line lead and tank to megger shall be as short as possible without joints and shall not touch tank or each other.

Testing procedure:
IR measurements shall be taken between the windings collectively (i.e. with all the windings being connected together) and the earthed tank (earth) and between each winding and the tank, the rest of the windings being earthed. Following measurements are relevant for Auto-transformer, three winding transformer and reactor.

Table 12.10

For auto-transformer	For shunt reactor	For winding transformer
HV/LV+E	HV/E	HV/LV+TV+E
IV/HV+E		LV/HV+TV+E
LV/HV+LV+E		TV/HV+LV+E
HV/IV		HV+TV/LV+E
IV/LV		LV+TV/HV+E
HV/LV		HV+LV/TV+E

HV **-** High voltage, IV **-** Intermediate voltage, LV-Low voltage, TV **-** Tertiary voltage windings, E – Earth

Record date and time of measurement, sl.no., make of megger, oil temperature and IR values at intervals of 15 seconds, 1 minute and 10 minutes. The live terminal of the equipment shall be connected to the winding under test.

Evaluation of Test Results

Check the IR values with the values given in the test certificate by the manufacturer. These values may be used as bench marks for future monitoring of the IR values. The IR values vary with the type of insulation, temperature, duration of application of voltage and to some extent on apply voltage. The IR values in air will be nearly 15 to 20 times more than in the transformer oil at the same temperature. The following table can be used for IR conversion with temperature.

Minimum insulation values for one minute resistance measurements for transformers may be determined by using the following empirical formula:
R = CE / √ kVA
Where
R - Insulation resistance in ohms
C - 1.5 for oil filled transformers at 20° C assuming that the oil is dry, acid free and sludge free.
E - Voltage rating in V of one of the single face windings (phase to phase for delta connected and phase to netural for wye connected transformers)
KVA - Rated capacity of the winding under test.
IR test results below this minimum value would indicate probable insulation breakdown.

i) The following IR values may be considered as the minimum satisfactory value at 30° C at the time commissioning, unless otherwise recommended by the manufacturer.

Table 12.11

Rated voltage class of winding	**Minimum desired IR value at 1 minute (MΩ)**
11 kV	300
33 kV	400
66 kV & above	500

Even if the insulation is dry, IR values could be low due to poor resistivity of the oil. The IR values increases with the duration of the application of the voltage. The increase in IR value is an indication of dryness of the insulation. The ratio of 60 second IR value to 15 second IR value is called absorption proportion

Polarisation index

For oil transformers with Class A insulation with reasonably dried condition polarization index at 30° C will be more than 1.3. Polarisation index test is the ratio meteric test, insensitive to temperature variation and may used to predict insulation system performance even if charging currents (i.e. capacitive, absorption or leakage currents) have not be diminished to zero. Since leakage current increases at a faster rate with the presence of moisture then does absorption current, the megohm reading will not increase with time as fast with insulation in poor condition as with insulation in good condition. The polarisation index is the ratio 10 minute to 1 minute megaohm readings. The values given below are guidelines for evaluating transformer
insulation:

$$\text{Polarisation index} = \frac{\text{10 min megger reading}}{\text{1 min megger reading}}$$

Table 12.12

Polarisation Index	**Insulation condition**
Less than 1	Dangerous
1.0 – 1.1	Poor

1.1. – 1.25	Questionable
1.25 – 2.0	Fair
Above 2.0	Good

Oil Leak Detection test - Pressure-Powdered Chalk Test

This test is used as a leak detecting means by some transformer manufacturers. The test piece is mounted in a tank in a manner similar to its actual application. All external surfaces are coated with a powerdered chalk and alcohol mixture. The tank is filled with oil, sealed and pressuized to the specified pressure. Oil leaks are easily detected as discolorations in the chalk. The test is typically run for 24 hours.
Four switch assemblies are mounted into a test tank simulating the standard mounting procedures. Once the switch assemblies are mounted, the tank is filled with transformer oil and sealed.
The external surfaces the switch and the tank in the vicinity of each switch are coated with the chalk-alcohol mixture. The tank is then pressuized to 7-10 psi and left for 24 hours. At the end of the 24 hours period, the chalk is inspected for signs of oil leak as evidensed by discoloratioin of the chalk. Four of the switch assemblies that were subjected to the helium leak test were tested using the powdered chalk pressure test.
No coloration of the chalk shall be observed after the 24 hourhold time. The assemblies must not leak.

Chapter-13

13 GENERAL AND PREVENTIVE MAINTENANCE

A power transformer in a sub-station is not only one of the costliest equipment but is also one of the most important links of the power system. If the power transformer is required to give a trouble free service it should receive proper attention for its maintenance. General maintenance, which is normally required to be done on transformers, is of two types
Reactive maintenance and Preventative maintenance

Reactive maintenance, also referred to as breakdown maintenance, is the most common form of equipment maintenance practiced in industry today. Equipment is neither serviced on a regular scheduled basis, nor is it tested to determine its condition. With this approach, equipment is repaired or replaced when a failure
occurs.
Preventative maintenance is a program of routine equipment inspections, maintenance tasks and repairs which are scheduled to ensure that degradation of equipment is minimized. A well designed preventative maintenance program slightly over-maintains equipment because scheduling is designed for the worst case
operating conditions. The overall objective is to prevent operating problems or failures, and ensure reliable operation of a facility.
Predictive maintenance is the technique of regularly monitoring selected parameters of equipment operation to detect and correct a potential problem before it causes a failure. This is done by

trending measured parameters which allows a comparison of current parameters to historical data. From this comparison, qualified judgments about the need for corrective action can be made. This approach ensures that the right maintenance activities are performed at the right time.

13.1 Importance of *Maintenance*

For many companies, maintenance is an activity which is carried out reactively, in response to interruptions, breakdowns and other unfortunate events. The ramifications of this kind of approach can be severe, especially at operations such as processing plants, assembly lines and power plants, where the failure of a relatively minor component can disrupt the entire facility. As many companies have found out, the total cost of downtime and emergency around-the-clock repairs can be staggering. On the other hand, a preventive maintenance program ensures continuity of operation and lessens the danger of unplanned
outages. Planned shutdowns take place during periods of inactivity or least usage, and as a result, troubles can be detected in the early stages and corrective action taken before extensive damage is done. The relationship between maintenance quality and electrical equipment breakdown can be seen in the Following results from a survey conducted by the IEEE I

Table 13.1

Number of Failures Versus Maintenance Quality For All Equipment Classes Combined			
	Number of Failures		
Maintenance Quality	**All Causes**	**Inadequate Maintenance**	**Percent of Failures Due to Inadequate Maintenance**
Excellent	311	36	11.6%
Fair	853	154	18.1%
Poor	67	22	32.8%
Total	1231	212	17.2%

13.2 Causes of electrical failure

There are four principal causes of electrical failure: dust and dirt accumulation; moisture; loose connections; and friction of moving parts. An effective maintenance program should aim to minimize these effects by keeping equipment clean and dry, keeping connections tight and minimizing friction.

DUST AND DIRT ACCUMULATION
Lint, chemical dust and the accumulation of oil mist and particles become conductive when combined with moisture on insulation. These can be responsible for degradation of insulation, tracking and flashovers.
Dirt build up on coils, in motors, transformers and relays will obstruct air flow and increase operating temperatures. This results in decreased efficiency and equipment failure. Contamination cannot be avoided in certain facilities such as steel mills, mines, foundries and aggregate plants. However, contamination in these environments can be minimized with regularly scheduled cleaning of equipment, and the use of properly designed apparatus such as encapsulated coils, totally enclosed self-cooled equipment and separate filtering systems.

PRESENCE OF MOISTURE
Moisture condensation in electrical equipment can cause oxidation, insulation degradation and connection failure. High humidity produces free condensation on the equipment which can result in short circuiting and immediate failure. Ideally, electrical equipment should be operated in a dry atmosphere, but often this is not possible, so precautions should be taken to minimize the entrance of moisture through the use of
proper enclosures and space heaters, where appropriate.

LOOSE CONNECTIONS
Electrical connections should be kept tight and torqued to recommended values. Creep or cold flow during load cycles is a major cause of joint failure. Hardware on all electrical equipment should be checked for looseness resulting from vibration and normal device operation. Cable connections and fuse clips are
common areas where loose connections can be found. Together with contactors and circuit breakers, they should routinely be inspected for tightness.

FRICTION
Friction can affect the freedom of movement of electrical devices and can result in serious failure or improper operation. In circuit breakers, friction can reduce speed of operation - a vitally important factor. Dirt on moving parts can cause abrasion and can result in improper operation such as arcing or burning.
Devices should not be lubricated unless specified by the manufacturer. The type and grades of lubricant specified should be strictly adhered to. Oil and grease collect dust and other contaminants, and also attack insulation, particularly rubber.

Checking the mechanical operation of devices and manually or electrically operating any device that seldom operates should be standard practice.

Correct interpretation of maintenance data from transformers is vital for increased reliability, long life, and advanced information on possible need of replacement.

Information accumulated through routine inspections and periodic tests on transformers in operation will usually provide you with a warning of approaching service problems. Then corrective measures can be taken. More importantly, if the available transformer maintenance records are effectively interpreted, it's not unusual for an impending failure to be predicted. This, in turn, allows appropriate replacement measures, alleviating the impact of a sudden loss.

Recognizing the warnings of impending failure requires careful surveillance of the records to seek out significant trends or aberrant behavior. Persistence and a basic knowledge of a transformer's expected operational characteristics will help you realize the full benefit of a maintenance program.

1. Regular inspection of the external surface of transformer for any dirt and dust and when required the same may be cleaned
2. Regular inspection of the external surface for any damages due to rust
3. Possible rust damages when noticed are to be removed and surface treatment restored in the original state by means of primer and finished paints for minimizing risk of corrosion and its subsequent spreading
4. Before carrying out any maintenance work ensure proper safety procedures as per utility practice and ensure the following:

a) The transformer and the associated equipment should be taken out of service, isolated and properly earthed

b) Obtain a permit to work / sanction for carrying out tests from the shift engineer

c) Obtain the keys for the transformer area

13.3 Checks to be carried out

Following checks may be carried out

1. Check for signs of corrosion
2. Check all joints for any sign of leakage
3. Check for any sign of mechanical damage
4. Check oil levels
5. Check that surrounding areas are clean and tidy

All results must be entered in the proper format for comparison during future tests.

Silica Gel Breather

Check the color of the silica gel breather so as to prevent any deterioration of silica gel breather. It is recommended to replace the same when half to two third of the silica gel has become saturated and become pink in colour. Failure to comply this will result in decreasing the drying efficiency of the breather. Silica gel breather could be reactivated while in its charge container or it can be emptied into a shallow tray. It is required to be heated in a well ventilated oven and a temperature of 130-138 degrees till the entire mass achieve the original blue color. Immediately after reactivation the new silica gel must be placed in a sealed container to avoid any absorbance of moisture while cooling.

Conservator Oil Level - Visual Checks

Visual checks may be carried out on regular basis for conservator oil levels. If the level is normal no action is required. In the event of above or below normal level action has to be taken to add or remove some of the oil. The correct oil filling level is normally is to be specified on the information plate. At a temperature of 45 degree C the conservator should be half filled. If the level shows the value full oil must be drained off. If it is low oil must be added immediately.

Check for Marshalling Cubicle and Kiosk

Following checks may be carried out and all results may be recorded in the format of comparison during future checks.

1. Condition of paint work
2. Operation of door handles
3. Operation of doors and hinges
4. Condition of door seal
5. Door switches working
6. Lights working
7. Heater working
8. Thermostats working
9. Operation of heating and lighting switches
10. Mounting of equipment secure
11. Manual operation of switches satisfactory
12. Checking of tightness of cable terminations
13. Checking of operation of contractors (isolating the trip signal, if any)
14. HRC fuses and their rating
15. Operation of local alarm annunciator by pushing push buttons provided for lamp test, acknowledge, reset, system test, mute etc. to cover all system function
16. Source change over test check by putting off power sources alternatively
17. Check for plugs for dummy holes and replacement, if found missing.

Note: Transformer / shunt reactor need not be taken out of service / isolated or earther while carrying out the above checks.

Valve Operation Checks

Following checks may be made either at the time of erection or after a major overhaul. All results must be recorded in the log for comparison during future tests.

1. Check each value for free operation
2. Check that each valve is padlocked where applicable
3. Check that each valve is adequately greased
4. Check that each valve returns to its "in service" operating position (open or closed)

Cooling System

Regular inspection may be carried out of the cooling surfaces and when required clean same from the dirt, insects, and leaves or any other air borne dirt. This is important as it affects the fan cooling. Cleaning is normally done by water flushing at high pressure. As regards cleaning of internal cooling surfaces, no major are considered necessary so long the oil is in good condition. In the event of setting of sludge formation of the oil the sludge may get deposited from the horizontal surfaces in radiators and coolers. The same may be flushed internally with clean oil in connection with oil exchange. In the event the sludge doesn't gets loosed the flushing may be done first with petrol and then with oil. However, this may be carried out in consultation with the supplier.

Regular inspection of the cooler banks may be made. The cooler can be cleaned by taking out the tube packets and thereby making them assessable for cleaning. For any increase in sound level of fan retighten all mounting supports.

Cooling System - Fans - Controls

Fan control are designed to operate both manually and automatically. The automatic function is related to the load and energization or both. The following controls are required to be checked.

1. **Manual Control -** Fan operation should observed after turning the switch to ON position for a brief period. Oil pump should be checked by observing the flow through gauges. In case of any malfunctioning manufacturers may be consulted.
2. **Temperature Control -** Remove the temperature bulbs from its well on the side / top of the transformer. Set the master controller to the automatic position. The temperature of the bulb should be slowly raised by using a temperature control calibration equipment for observe for proper calibration / operation.
3. **Load Control -** Check the secondary current of the controlling CT for proper operation. Shot the secondary of CT (if the transformer is energized). Remove the secondary lead from the control circuit and inject the current to the control circuit. Vary the level of the current to observe the proper operation.

Cooling System - Fan - Visual Inspection

Following visual inspection checks may be carried out without taking a shut down of the transformer to check that the fans are operating at a designed speed, airways are not blocked and guards and blades are not damaged.

1. Visual check for contamination of motor and fan blades
2. Check for build up of moisture in the motor
3. Check bearing lubrication
4. Check for correct rotation
5. Check for unusual noises
6. Check for corroding parts

Cooling System - Pumps-Visual Checks

Following visual inspection checks may be carried out without taking a shut down of the transformer

1. The transformer and associated equipment need not be out of service or isolated while carrying out visual checks on the pumps.
2. Obtain a 'Permit to Work' from the Shift Engineer
3. Obtain keys to the transformer compound and marshalling kiosk
4. All results must be recorded in a log for comparison during future tests in service.
5. Following checks should be carried out

a) Check for correct rotation
b) Check for unusual noises/abnormal vibration - replacement of rotor and bearings
c) Check for corroded parts
d) Check for electrical problems

Winding Temperature Indicators – Test

Following tests may be carried out:

Cooler control, alarm and trip test

1. Temperature indication calibration of WTI bulb
2. Secondary induction test

Before carrying the tests it may be ensure that the transformer and the associated equipment is de-energized, isolated and earthed.

Cooler control, alarm and trip test

The setting of temperatures should be as per the approved scheme. The values given below are indicative values. However, these values are not to be taken for granted and are to be verified with manufacturers instruction manual.

1. Access the local winding temperature indicator and set the temperature indicator pointer to the first stage of cooling value (65 degree C).

Check that the fans of those coolers set to first stage are operating.

- Set the temperature indicator pointer to second stage cooling value (80 degree C).

Check that the fans of those coolers set to second stage are working.

- Set the temperature indicator pointer to the alarm value (110 degree C).

Check with the control room that the alarm signal has been received.

- Set the temperature indicator pointer to the trip value (125 degree C).

Check with the control room that the trip signal has been received

Temperature indication calibration of Winding Temperature Indicating (WTI) bulb

Remove the WTI bulb from the transformer pocket and insert the bulb into the calibrated temperature controlled bath.

Raise the temperature of the bath in 5 degree steps and check the response of the WTI after 10 minutes. This may be continued up to a maximum temperature of 130 degree C. The tolerance permitted for temperature indication is ± 3 degree C.

Lower the temperature of the bath in 5 degree step and check the response of the temperature indicators after 10 minutes. At the same time check the transducer output. The tolerance indicated for temperature indication is ± 3 degree C.

Check the alarm and trip switch setting by rotating the pointer slowly to the set temperatures. These settings will be indicated using a multi-meter. Record the values at which the switches operated.

Once these checks are completed return the bulb to the pocked in the transformer cover. Do not forget to bring the maximum level pointer to match the temperature indicator.

Oil Temperature Indicator - Test

Remove the OTI bulb from the pocket on the transformer lid and insert them into the calibrated temperature controlled oil bath.

Increase the temperature of the oil bath in 20 degree C steps from O degree C up to a maximum temperature of 120 degree C. Check and record OTI readings against bath temperatures up the range (tolerance ± 3 degree C).

Access the oil temperature indicator and rotate the pointer slowly to the alarm value (95 degree C) and the trip value (110 degree C) and check their operation. Using a resistance meter, across the switches.

Gas and Oil Actuated Relay - Test

The use of gas operated relay as protection for oil-immersed transformers is based on the fact that faults as flashover, short-circuit and local overheating normally result in gas-generation. The gas-bubbles gathering in the gas-operated relay affect a flat-controlled contact that gives an alarm signal.

Following tests may be carried out:

1. Gas and oil relay inclination (Only at the time of pre-comissioning)
2. Gas and oil relay alarm
3. Gas and oil relay trip
4. Gas and oil relay surge at pump energization

Before conducting above tests ensure that transformer and associated equipment is de-energized, isolated and earthed.

Check the stability of the alarm and trip contacts of the buchholz relay during oil pump start by both manual and automatic control to ensure spurious alarms and trips do not result.

13.4 Maintenance and testing procedures

Insulation measurements shall be taken between the windings collectively (i.e. with all the windings being connected together) and the earthed tank (earth) and between each winding and the tank, the rest of the windings being earthed. Following measurements are relevant for Auto-transformer, three winding transformer

Bushsings

Regular cleaning of the bushing porcelene from dirt and dust should be carried out in the areas where the air contains impurities such as salt, cement, smoke or chemical substances, the frequency may be increased.

Connectors

To avoid prohibited temperature rise in the electrical connection of the transformer, all screw joints should be checked and retightened. Use of thermovision camera may be made for any hot-spots in the joints.

Maintenance of Insulating Oil

One of the most important factor responsible for the performance of the transformer is the quality of the oil. Normally insulating oil is subjected to dielectic and moisture contents at site for monitoring the condition of the oil.

Test for dielectric strength (BDV)

Using a BDV test kit, adjust the electrodes **(12.5 mm dia)** sot that a gap of **2.5 mm** is between them. Carry out six tests on the oil, stirring the oil between each breakdown and allowing it to settle. Take the average result of the six figure and this should be used for acceptance criteria (i.e. 60 kV)

Table 13.2

For auto-transformer	For winding transformer
HV/LV+E	HV/LV+TV+E
IV/HV+E	LV/HV+TV+E
LV/HV+LV+E	TV/HV+LV+E
HV/IV	HV+TV/LV+E

IV/LV	LV+TV/HV+E
HV/LV	HV+LV/TV+E

Note.: HV **-** High voltage, IV **-** Intermediate voltage, LV**-**Low voltage, TV **-** Tertiary voltage windings, E – Earth
Record date and time of measurement, sl.no., make of megger, oil temperature and IR values at intervals of 15 seconds, 1 minute and 10 minutes. The live terminal of the equipment shall be connected to the winding under test.

using the following empirical formula:

R = CE / √ kVA
Where
R - Insulation resistance in ohms
C - 1.5 for oil filled transformers at 20° C assuming that the oil is dry, acid free and sludge free.
E - Voltage rating in V of one of the single face windings (phase to phase for delta connected and phase to netural for wye connected transformers)
KVA - Rated capacity of the winding under test.

The following IR values may be considered as the minimum satisfactory value at 30° C at the time commissioning, unless otherwise recommended by the manufacturer.

Table 13.3

Rated voltage class of winding	**Minimum desired IR value at 1 minute (MΩ)**
11 kV	300
33 kV	400
66 kV & above	500

The full details of the IR and othe tests are given in the above section of Transformer testing

Tests for moisture content (ppm)

Using an automatic moisture content test set and a suitable syringe that has been flushed, inject a sample of the oil into the test set. Depending upon the make of the test set the moisture figure may be indicated by mg H2O. if this is the case the figure may be divided by weight of the sample injected in grams. This will give in parts per million (ppm). Typically the moisture content should be less than 15 ppm for transformers in service.

Prior to energisation of transformer, the oil sample shall be tested for properties and acceptance norms as given in Table 3.

Table 13.4

S.No.	Particulars of test	Acceptable value
1.	BDV (kV rms)	60 kV (Min.)
2.	Moisture content	15 ppm (Max.)
3.	Tan delta at 90˚ C	0.05 (Max.)
4.	Resistivity at 90˚ C	1*10 : -cm (Min.)
5.	Interfacial tension	0.03 N/m (Min.

13.5 Maintenance tests recommended

Measurement of Insulation Resistance

The measurement of insulation resistance is carried out to check the healthiness of the transformer insulation. This test is the simplest and is being widely used by the electrical utilities. This test indicates the condition of the insulation i.e. degree of dryness of paper insulation, presence of any foreign containments in oil and also any serious defects in the transformer. The measurement of insulation resistance is done by means of megger of 2.5 kV for transformer windings with voltage rating of 11 kV and above and 5 kV for EHV transformers.

All safety instructions have to be followed as per the utility practice before carrying out this test. It has also to ensured that high voltage and low voltage windings are isolated along with the concerned isolaters. In case transformer is having a tertiary windings, ensure the isolation are the same prior to commencement of the test. Also the jumpers and lighting arrestors connected to the transformer have to be disconnected prior to start of testing after issue of PTW/SFT.

Following precautions may be taken while conducting the above test.

1. Bushing porcelain may be cleaned by wiping with a piece of the dry cloth.
2. When using a megger, observe the usual accident preventive rules.
3. As the windings possess a substantial capacitance, the current carrying cords should only be touched after the electric charge have been removed from them.
4. Connecting wires from the bushing line lead and tank to megger shall be as short as possible without joints and shall not touch tank or each other.

Inspection / Maintenance of Tap Changer

Generally the temperature of OLTC compartments is a few degree Celsius less than the main tank. In case the temperature is found to be higher than this indicates a sign of internal problem and the OLTC compartment need to be opened. Prior to opening of OLTC compartment the same should be thoroughly inspected for external symptoms of potential problems. Also, inspect the integrity of paint, weld leakes, oil seal integrity, pressure release device and liquid level gage prior to opening of OLTC.

Following de-engerisation, close all the walls between oil conservator, transformer tank and Tap Changer head. Then lower the oil level in diverter switch oil compartment by draining the oil for internal inspection. Upon entering the OLTC compartment check for gaskit deterioration if any, compartment floor for any debris which may indicate abnormal wear.

Following items may be checked and manufacturer's engineer consulted for details of maintenance.

1. Function of control switches
2. OLTC stopping on position
3. Fastener tightness
4. Signs of moisture such as rusting, oxidation or free standing water
5. Mechanical clearances as specified by manufacturer's instruction booklet
6. Operation and condition of tap selector, changeover selector and arcing transfer switches
7. Drive mechanism operation
8. Counter operation
9. Position indicator operation and its co-ordination with mechanism and tap selector position
10. Limit switch operation
11. Mechanical block integrity
12. Proper operation of hand-crank and its interlock switch
13. Physical condition of tap selector
14. Freedom of movement of external shaft assembly
15. Extent of arc erosion on stationary and movable arching contacts
16. Inspect barrier board for tracking and cracking
17. After fitting with oil, manually crank throughout entire range
18. Oil BDV and moisture content (PPM) to be measured and recorded

Finally, the tap selector compartment should be flushed with clean transformer oil carbonization which may have been deposited should be removed. Min BDV should be 50 kV and moisture content should be less than 20 PPM.

Importance of variations in sound level

The audible sound level of a transformer, either dry-type or liquid-filled, is largely dependent on the ratio of the applied voltage to the number of active turns in the primary winding (volts per turn) or on the degree of distortion in the load current. To a lesser degree, it's dependent on the tightness of core and coil clamping components and the external tank structure.

If a noticeable change in sound level is detected that cannot be explained by changes in loading practices, your first check should be the input or output voltage on the transformer because its sound level is very sensitive to changes in voltage. If the voltage increases, the sound level will also increase.

As such, you should verify that the measured voltage is within the nameplate rating for the tap setting on the transformer. If it consistently exceeds the tap voltage by more than 5%, the transformer is over-excited and should be de-energized and a tap selected that is within 5% of the applied voltage.

Transformers designed to existing standards can be safely operated at overvoltages of up to 5%, but the sound level will increase noticeably.

If the applied voltage is within the range of the tap setting on the transformer, and there is an unexplained increase in sound level, there could be internal damage that has shorted one or more winding turns in the primary winding. This would reduce the effective number of turns and increase the volts per turn and the sound level. If this problem is suspected, the transformer should be removed from service for acceptance tests. For liquid-filled transformers, if these tests are inconclusive and the unit is to remain in service, oil samples should be taken for gas-in-oil analysis on at least a monthly basis until the analyses refute or confirm the internal winding problems.

An increase in sound level can also be the result of load current distorted by harmonics. Check the connected load for any changes. There may possibly be a developing problem with a load component that has introduced load distortion on the transformer. As various load segments are switched in and out, listen to the sound level for any abrupt changes. Load current with a high harmonic content can cause higher temperatures than the designer anticipated in the magnet core or in the windings. If any noticeable increase in sound level is caused by load harmonics, you should take steps to minimize or eliminate the additional loading on the transformer.

Evaluating tank heating

Hot spots on the tank surfaces of liquid-filled transformers, or enclosures of dry-types, that are severe enough to blister or discolor the paint may indicate the existence of open or shorted internal lead connections. These deficiencies may create changes in the current paths, resulting in induced currents in the tank wall. When tank heating occurs, the transformer should be deenergized as soon as possible and electrical tests performed. Winding resistance and impedance measurements are especially important when tank heating is observed, as changes in these characteristics will indicate changes in the internal connections.

For liquid-filled transformers, an oil sample should be taken for gas-in-oil analysis. If tank heating persists, or a gas-in-oil analysis indicates an increase in combustible gas above the limits shown in Fig. 1, an internal inspection should be made to observe any evidence of irregularities in the internal connections. If a defective connection is identified, an experienced repair organization may be able to make a field repair and recondition the transformer. The surface of the oil should be examined for evidence of carbon or burnt insulation. If the oil is discolored to the point that the internal parts cannot be seen, the transformer should be removed to a repair facility for untanking and examination.

Transformer oil maintenance

First, when reference is made to oil (askarel), this is done in a generic sense and the term relates to a group of synthetic, fire-resistant, chlorinated, aromatic hydrocarbons used as electrical insulating liquids.These liquids serve as a heat transfer medium. If a liquid-filled transformer is equipped with a pressure gauge, pressure readings should be taken during those times when top-oil temperature readings are taken. Comparison of the pressure readings should be noted on a regular basis and correlated to the temperature readings. Whether a transformer has a pressure gauge or not depends on the type of oil preservation system. The general types of oil preservation systems are as follows.

* Free Breathing. These transformers have vents above the oil that allow air to enter and exit as the oil expands and contracts due to variations in the operating temperature.

* Sealed. A sealed transformer does not have vents but is designed to withstand the internal pressure

variations resulting from the compression of the gas space above the oil as the oil volume changes due to thermal expansion and contraction.

* Conservator. These type transformers have a main tank that is completely filled with the insulating liquid and a separate external reservoir. This external tank is provided with a quantity of fluid slightly greater than that displaced by the expansion and contraction of the insulating fluid in the main tank. The external tank is mounted above the main tank and is connected by a short pipe that allows the insulating liquid to flow back and forth.

* Automatic gas seal. Transformers of this type have a space filled with nitrogen above the liquid. The open space is connected to a nitrogen bottle and a regulator. The regulator bleeds off nitrogen from the transformer tank when the liquid rises and adds nitrogen when the liquid falls. This procedure maintains the internal gas pressure within an allowable range.

In addition to the above types, there are other variations. Most transformers in commercial applications are either free breathing or sealed. A sealed unit will usually have a pressure gauge. But, a free breathing unit will not.

A sealed transformer with a welded-on cover should maintain a consistent relationship between top-oil temperature and pressure. If a review of the maintenance record indicates that periods of maximum temperature do not have correspondingly high pressure readings (with minimum pressure readings at lowest temperatures), a leak in the gas space should be suspected. If the peaks and valleys of the pressure readings do correspond to similar peaks and valleys in the temperature readings but the values of the pressure readings are declining over time, you should check the liquid level for loss of fluid and inspect the transformer for fluid leaks.

Many sealed units with bolted-on covers and gasket seals will lose gas pressure if a positive pressure is maintained for an extended period of time. These same units may allow the entrance of air if a negative pressure is maintained over an extended period. Concern in regard to this condition should depend on the ambient weather conditions (humidity, precipitation, and airborne contamination), and the degree of cyclic variations in oil temperature. Be careful not to create conditions that will draw moisture or other contaminants into the transformer through a leak.

When conditions exist that would tend to allow the entrance of contaminants, and the pressure readings indicate a leak, the transformer should be deenergized and a pressure test performed. Most leaks can be found and effectively sealed; however, large gasket areas, especially those using cork or composition gaskets, will often allow the gradual decline of gas pressure, even though an identifiable leak cannot be found.

When operating transformers with minor gas leaks, you should closely monitor oil tests of the fluid dielectric and water content. If there is no noticeable deterioration, the concern for a gradual loss of gas pressure should be minimal.

Significance of liquid level

For liquid-filled transformers, the liquid level should vary with the top-oil temperature, as the tank pressure varies with a sealed transformer. If the indicated liquid level pattern does not follow the rise and fall of the top oil temperature, you should investigate for oil leaks. If none can be found, you should check the liquid level gauge's operation at a convenient outage.

The liquid level should not descend below the minimum indication on the gauge or rise above the maximum indication during extremes of operating conditions. If these limits are exceeded, you should consult the manufacturer or instruction book to establish the proper oil level and the existing level should be checked at the earliest available outage.

If the oil level is consistently below the minimum indication, the transformer should not be operated until the internal level is checked to ensure that no live parts are exposed above the fluid and that the minimum oil level reaches the upper tank opening of any existing external cooling radiators.

You should carefully follow the manufacturers' instructions when adding oil to a transformer. If the instruction book cannot be located, the manufacturer should be contacted as there are often critical variations in the replenishment fluids used, and the manner in which they are introduced to the fluid already in the transformer.

Oil temperature interpretation

For liquid-filled transformers, an operating temperature above normal limits can be indicative of internal problems with the core and coil components, or with the normal exchange of heat from the core and coil assembly to the surrounding air. However, an understanding of what should be the normal operating temperature of a transformer often leads to confusion. Most liquid-filled transformers are rated with a temperature rise of either 55 [degrees] C or 65 [degrees] C. This rated temperature rise will be printed on the nameplate and is defined in various standards as the average winding temperature rise above ambient. The temperature rise must therefore be added to the ambient or surrounding air temperature to arrive at the expected full-load temperature for existing conditions.

Even with the understanding that the nameplate temperature rating is an average winding temperature rise above ambient, there is no gauge on a transformer that measures the average winding temperature because it cannot be directly measured. It can only be measured through a series of tests that would be impractical to make outside a factory test installation. The temperature measured on the gauge is the top-oil temperature and sometimes a simulated winding temperature. Both of these measurements will indicate the temperature rise plus the ambient.

The important point to note here is that the nameplate temperature rise is not the temperature one sees on the temperature gauge of a transformer when operating at full load. The rise in gauge temperature cannot be precisely correlated to the nameplate temperature rise with the information available to most users. But, this correlation can be approximated if the transformer is operating correctly. The relationship between the measured top-oil temperature and the average winding temperature varies somewhat from design to design but usually the top oil-temperature will be 5 [degrees] C to 10 [degrees] C lower than the average winding temperature. The winding temperature indicator, if one is provided, will usually read the winding's hottest spot temperature, which is from 5 [degrees] C to 10 [degrees] C higher than the average winding temperature. Remember that all measured temperatures must have the ambient temperature subtracted to come up with the temperature rises referred to on the nameplate and in the standards

Another variable that confounds analysis of temperature readings is the time delay experienced between a change in load, or a change in ambient temperature, and the eventual transformer temperature change. The time to reach a temperature equilibrium following a change in either or both of these conditions can be 4 hrs or more for a typical transformer in a commercial application. Therefore, you should compare temperature readings at the same time of day. If done, the variables will be minimized, assuming that the patterns for load variations and changes in ambient temperature are somewhat consistent for corresponding time periods.

The effect of varying ambient temperature over long time spans can be eliminated in large part if the ambient temperature is recorded so that it may be subtracted from the temperature values read on the gauges.

If temperatures under similar load conditions are showing an increase when ambient temperatures are subtracted, you may have thermal problems developing in the transformer and acceptance tests, including winding resistance measurements and dissolved gas analysis, should be performed and compared with prior tests.

Performing oil tests

Oil tests can be separated into two general categories; those that assess the immediate serviceability of the oil and those that assess the degree of aging.

To evaluate the immediate serviceability of the oil, two important tests are carried out: determination of dielectric strength and determination of water content. You should review these test measurements to verify no sudden changes that would indicate the possibility of the entrance of moisture or other contaminants. If there is a sudden change, the transformer should be carefully inspected for leaks and the oil processed if the dielectric is below the 28kV level, or water content is above 30 ppm (parts per million). You should refer to the manufacturer's instructions for oil processing practices appropriate for the transformer.

The principal indicators to assess the degree of aging of the insulation system (lead conductor insulation, winding insulation, core insulation, and the fluid insulation) are interfacial tension, color, and acidity. These indicators should be reviewed for any abrupt changes as they would normally change very little from year to year. A significant change in these values may indicate overheating of all or part of the insulation system.

If there is an interfacial tension decrease of 20% or more, or an acidity increase of 25% or more (with a change in the color of at least one full point on the ASTM-D1500 color scale between annual readings), the oil should be re-sampled and tested for confirmation of the results. These abrupt changes denote an accelerated aging of the insulation system, which would be indicative of overheating of the insulation.

The transformer should be scheduled for acceptance tests as soon as possible if these results are verified.

Gas-in-oil analysis

As a liquid-filled transformer insulation system ages, the oil and paper gradually deteriorate, producing combustible gases that are dissolved in the oil. Study of these gases has led to the recognition of the products of normal aging as well as certain combinations of gases that, in sufficient quantities, can provide warning of developing problems. Performing a gas-in-oil analysis provides a valuable maintenance tool, especially if done on a regular basis, so that normal trends for each transformer can be established. The laboratory report of the test results will list the key combustible gases detected and their quantities expressed in ppm.

Fig. 1 (see page 54), taken from the Guide for Interpretation of Gases Generated in Oil-Immersed Transformers (ANSI/IEEE C57.104), lists the 90% probability norms of combustible gas levels for transmission rated transformers (normally 115kV and higher). These values should be used as a guide only. There is no universal agreement among experts on limits for particular gases; as such, it's important to establish normal trends for individual transformers.

Similar norms have not been established for lower voltage transformers as a separate category. However, experience is accumulating that indicates the limits shown in Fig. 1 are suitable guidelines that may be used for lower voltage transformers (4.16kV to 34kV).

The most important gas to note is acetylene (C_2H_2). This gas requires arcing for its production and levels above 35 ppm should be investigated. Ethane and ethylene are next in order of concern and indicate an intense hot spot. If an elevated level of carbon monoxide is also detected, paper insulation is involved in the hot spot. Elevated levels of methane without correspondingly high values of ethylene and ethane indicate a hot spot of less intensity. The presence of a high level of carbon monoxide would again indicate that paper insulation was involved. Hydrogen indicates that corona is present in the oil. Corona results from the partial breakdown of oil when it is electrically stressed to a critical value. Hydrogen theoretically should be a key gas in maintenance analysis but, in practice, the level of hydrogen varies so widely from test to test that its usefulness is obscure.

If the limits in Fig. 1 are exceeded, or if established trends for a particular transformer suddenly change, the transformer should be acceptance tested.

ANSI/IEEE C57.104 and its references give complete information on interpreting gas analysis data and should be consulted for more information on this subject.

Insulation resistance measurements

Insulation resistance tests taken with a megohm meter are valuable maintenance measurements since they are easy to make with portable instruments and may be effective in finding defective insulation. However, on liquid-filled transformers, these readings are often erratically variable from test to test. There may be a measurement range as much as 50%. The variations are due in large part to the nature of the insulating oil that takes into solution substances that tend to polarize under the application of the DC voltage stresses produced by the megohm meters. Insulation resistance measurements on dry-type units are usually more consistent, and therefore, more useful than on liquid-filled transformers. Another significant factor affecting megohm readings of liquid-filled units is that there are various combinations of solid and liquid insulations that are used in transformer construction.

An additional factor to consider when measuring insulation resistance is the temperature of the transformer because heat affects each material differently. Insulation resistance is usually measured when the transformer is cooling down. But when doing so, a problem exists in that each material cools at a different rate. The dual uncertainty of the exact temperature of each insulation component, and the degree to which its resistance variation affects the overall reading, makes temperature correction of the megohm values very imprecise. Because of these variations, trends in insulation resistance readings within [+ or -]50% are seldom significant and should always be supported with other tests such as dissolved gas analysis, measurement of oil dielectric strength, and determination of water content.

Meaning of changes in power factor

Power factor measurements are not usually recommended for dry-type transformers. If insulation power factor measurements are carried out for a liquid-filled transformer, and corrections are made for temperature according to the instructions for the particular test set, the measurements should show little variation over long periods of time. If there is a sudden increase in the reading, or if it exceeds 2%, obtain an oil sample for water content measurement, dielectric strength measurement, and color evaluation.

High power factor readings are usually caused by moisture in the insulation system. If oil tests indicate the water content is less than 30 ppm, the color of the sample is acceptable, and the dielectric strength is good, a high water content in the insulation system is unlikely. Clean the external bushing surfaces and check for cracks or other defects. If no bushing defects are identified, take an oil sample for dissolved gas analysis and review the results for any abnormality.

If the above steps do not give an explanation for the high power factor, return the transformer to service. Then, sample the oil for dissolved gas analysis on a monthly basis until the absence of increasing combustible gas indicates the transformer is performing normally. At that point take a careful reading of the power factor and suspend testing until the next periodic maintenance is scheduled. At that time take another reading of the power factor to see what change has taken place.

Because transformers are usually very reliable, it's easy to forget to carry out routine maintenance procedures. But recognizing that a transformer can represent a relatively sizable capital expenditure, that these units are a critical component in providing dependable electrical service, and that a safe electrical system includes transformers operating correctly, it's important to take the time and effort to properly maintain this type equipment.

The full value of a maintenance program can be realized by reviewing accumulated maintenance data with the above guidelines in mind. Simple routine observations and measurements, which should be made and recorded on a regular basis, can provide valuable insights into the internal operation of most transformers. The disciplined review of these observations along with periodic tests such as oil evaluation, insulation resistance measurements, and sometimes dissolved gas analysis, can give optimum assurance that a transformer is not being allowed to fail due to a correctable defect. These measures will also increase the likelihood of recognizing the inevitable approach of a failure due to a cause that might not be correctable. This knowledge will allow preparation for a scheduled changeout of the defective transformer and eliminate the chaos and expense that usually accompany an unplanned outage.

Annexure - A

OIL SAMPLING PROCEDURES

Scope:

This procedure describes the techniques for sampling oil from oil filled equipment such as power transformer and reactors using stainless steel sampling bottles fitted with valves on both sides.

Apparatus:

i) Stainless steel sampling bottle of volume one litre as per IS 9434 - 1992
ii) Oil proof transparent plastic or transparent PCV tubing
iii) A drilled flange in case sampling valve is not suitable for fixing a tube

Sampling Procedure: (Refer Fig. -----)

1. Remove the blank flange or cover of the sampling valve and clean the outlet with a lint free cloth to remove all visible dirt.
2. If the sampling valve is not suitable for fitting a tube, it may be necessary to use a separate flange with a nozzle in the centre suitable to connect the transparent plastic / PVC tube (refer Fig.-----------).
3. Connect a short oil proof plastic tube (around one meter long) at both end of the stainless steel sampling bottle (5) as shown in (Fig&ldots;&ldots;&ldots;&ldots;).

4. Open the valves (4) and (6) on the stainless steel bottle (5), allow 250 ml (approx.) of oil to flow into the bottle by opening value (1). Close (4), (6) and (1). Disconnect tube from the flange and rinse by gently tilting the bottle upside down such that no air bubble is formed inside during rinsing. Expel this oil into the waste bucket ;(7) by opening valves (4) & (6)
5. Connect the tube (3) to the flange (2). Hold the bottle in vertical position as shown in Figure (&ldots;&ldots;). Slowly open the equipment-sampling valve so that oil flows through the sampling bottle.
6. After stainless steel sampling bottle (5) has been completely filled with oil, allow about one litre to two litres of oil to flow to waste bucket (7), till no air bubbles are seen from top outlet.
7. Stop the oil flow by closing of first the valve (6) and then valve (4) and finally the sampling valve (1).
8. Disconnect the sample bottle (5) and then disconnect the tubing from the main equipment and the sampling bottle.
9. Label the sample (Refer annexure AI).
10. Send the informations as per as per Annexure - AII along with the samples.
11. In case of critical samples furnish information as per Annexure - AIII

Precautions:

1. When sampling oil, precaution should be taken to deal with any sudden release of oil
2. Sample should normally be drawn from the bottom-sampling valve.
3. Proper closing of both the valves (4) & (6) of the bottle should be ensured immediately after the collection of sample.
4. Due care should be taken to avoid exposure of oil to air while sampling.
5. Sampling should be done preferably in a dry weather condition.
6. Sample should be taken when the equipment is in its normal operating condition.
7. Care should be taken to hold the bottle in place inside the container when transporting.
8. Testing should be carried out as early as possible.

Annexure AI

Labling of the Oil Sample Bottle

a. Bottle Number.................. :
b. Company Name.................:
c. Substation Name...............:
d. Equipment Name or ID No... :
e. Sampling date..................:

Annexure - AII

Details to be Furnished along with the Samples

1. Bottle Number..:
2. Name of Substation...:
3. Equipment Name/Identification No...:
4. Date of sampling...:

5. Oil temperature..:
6. Winding Temperature...:
7. Load (in case of transformer) or Voltage (in case of reactor).......:
8. Date of last filtration..:
9. Oil top up (if any)..:
10. Manufacturer's serial number..:
11. Weather condition..:

In Case of New transformer/reactor following additional informations to be furnished

12. Date of commissioning..:
13. MVA/MVAR rating...:
14. KV rating..:
15. Oil type (Parafinic/Napthanic)..:
16. Cooling (ONAN/ONAF/OFAF)...:
17. Type of oil preservation (Air Cell/Diaphragm type/Direct breathing):
18. Make.. :

Annexure - AIII

DATA INPUT FORMAT FOR CRITICAL EQUIPMENTS

1. Voltage profile for last Six months indicating maximum and minimum values and % of time voltage more than rate voltage.

2. Loading pattern (Monthwise) of the transformer for last six months

Max. Load	Current (A)	MW.......	MVAR.....
Max. Load	Current (A)	MW.......	MVAR.....
Normal Load	Current (A)	MW.......	MVAR.....

3. Date of last filtration carried out

4. Type of oil preservation system:
Air cell in conservator/diaphragm in conservator/Direct Breathing

5. Any Buchholz Alarm / trip Operation in Past:	Yes/No
6. Any oil topping up done in the past:	Yes/No

7. Whether complete oil was changed any time: Yes/No

8. Present BDV/Moisture content value:

9. Color of Silica gel

10. Date of Commissioning:

11. Manufacturer's Serial Number:

Annexure - B

TRANSFORMER DATA SHEET SMALL TRANSFORMERS

Customer Name: _______________________

Project/Quote Number: ________ Item No.___

KVA Rating:

Frequency: 50 HZ 60 HZ

Impedance: %

Winding Temperature Rise: (Standard) ˚C / ˚C

Primary Voltage (KV) :

Primary Taps: Standard (± 2-2 ½)) :

Primary BIL (KV):

Primary Connection Delta or Wye :

Primary Termination Switchgear throat Bus Duct Air Terminal Chamber :

ANSI Segment:

Secondary Voltage (KV):

Secondary BIL (KV) :

Secondary Connection Delta Wye :

Secondary Termination Switchgear throat Bus Duct Air Terminal Chamber :

ANSI Segment:

Secondary Bushing Arrangement Standard (X1-X2-X3-X0 X0-X1-X2-X3) :

Secondary Termination Location Right Left :

Insulating Fluid :(Mineral oil Silcone fluid) :

Application Location: Indoor Outdoor :

Forced Air Rating (OA OA/FA OA/FFA)

Sound Level Standard ____ Special ________

Special Tests: Witness__ Temperature __ Impulse QC __ ANSI __ Sound __

Drawings: Standard ____ Reproducible _____ Electronic DXF File _______.

Other Special Instructions:

Annexure - C

TYPICAL TECHNICAL PARTICULARS FOR A 315 MVA, 400/220/33KV TRANSFORMER

AUTO - TRANSFORMER			
S.No.		PARTICULARS	RATINGS / VALUES
1		Name of the manufacturer, address and country	M/s. ABC
2		Governing Standards	IS-2026, IEC-60076
3		Service (Outdoor/Indoor)	Out door
4		Rated frequency (Hz)	50 Hz
5		No. of phases	Three
6		Type of cooling	ONAN/ONAF/OFAF
7		No. of windings	Three
8		Rating (MVA)	HV IV LV
	i)	With ONAN cooling	189 189 63 MVAR+3 MVA
	ii)	With ONAF cooling	252 252 84 MVAR+4 MVA
	iii)	With OFAF cooling	315 315 105 MVAR+5MVA

9	a)	Rated voltage (KV) (HV/IV/LV)	400/220/33
	b)	Short circuit withstand level (kA) and duration (sec)	As per IS & 2 sec., HV & IV side system fault level is 40kA
10		Connection symbol	YN, a0, d11
11		Temperature rise of oil above reference peak ambient temperature of 50 deg.C	
	i)	At full ONAN rating	50 deg.C
	ii)	At full ONAF rating	50 deg.C
	iii)	At full OFAF rating	50 deg.C
12		Temperature rise of windings, above reference peak ambient temperature of 50 deg.C	
	i)	At full ONAN rating	55 deg.C
	ii)	At full ONAF rating	55 deg.C
	iii)	At full OFAF rating	55 deg.C
13		Temperature gradient between windings and oil	Approx. 15 deg.C
14		Limit of hot spot temperature for which transformer is designed.	98 deg.C at an average waighted yearly ambient of 32 deg.C

S.No.		PARTICULARS	RATINGS / VALUES
15		Time in minutes for which the transformer can be run at full load without exceeding the max. permissible temperature at reference ambient temperacture of 50 deg.C when	
	a)	Supply to fans is cut off but the oil circulating pumps are working	20 minutes
	b)	Supply to oil circulation pump is cut off but the fans are working	20 minutes
	c)	When supply to both the fans and the oil circulating pump is cut off	10 minutes
16	a)	Guaranteed "No load losses" at rated voltage, normal ratio and rated frequency and 75 deg. C average winding temperature (kW)	80 KW Max.

	b)	State whether the losses are firm or subject to tolerances. Incase it is subject to tolerance indicate the ceiling for tolerances.	Firm
17	a)	Guaranteed load losses at rated output, rated frequency corrected for 75 deg. C winding temperature for the: (KW)	
	i)	Principal tap	500 KW Max.
	ii)	Lowest tap	600 KW
	iii)	Highest tap	550 KW
	b)	16.(b) as above.	Firm
18	a)	Guaranteed cooler losses at rated output, normal ratio, rated voltage, rated frequency at ambient temp. of 50 deg. C (KW)	14 KW Max.
	b)	16.(b) as above	Firm
S.No.		PARTICULARS	RATINGS / VALUES
19		Over excitation with stand time	
	i)	125%	60 Sec.
	ii)	140%	5 Sec.
	iii)	150%	1 Sec. approx.
20		Positive sequence impedence on rated MVA base, rated current and frequency and 75 deg. C winding temp at	HV-IV HV-LV IV-LV
	i)	Principal tap (%)(HV/IV, HV/LV, IV/LV)	12.5±10% 45+15% 30+15%
	ii)	Highest tap (%)	12.25 app. 45 app. 30 app.
	iii)	Lowest tap (%)	13.0 app. 45 app. 30 app.

21		Zero sequence impedence at principal tap (%)	0.9 to 1.0 P.U. of positive sequence impedance.
22		Leakage reactance for HV, IV and LV	Same as clause 20.0
23		Capacitance to earth for HV, IV and LV	7500 pF, 7500 pF, 18000 All are approx. values
24		Efficiency at 75 deg. C winding temperature on:	At Unity Power Factor
	i)	100% load	99.82
	ii)	75% load	99.85
	iii)	50% load	99.87

S.No.		PARTICULARS	RATINGS / VALUES
25		Regulation at full load at 75 deg. C expressed as percentage of normal voltage, at	
	i)	Unity (1.0) Power factor (P.F)	0.93
	ii)	0.85 PF (lagging)	7.28%
26		CORE DATA:	
	i)	Material for core laminations Governing Standards & corresponding grade	HI-BI, AISI Standard CRGO
	ii)	Thickness of laminations	0.27 mm Approx.
	iii)	Insulation between core laminations	Inorganic Insulation
	iv)	Insulation of core bolts, washers and plates etc.	Core bolts-Fiber Glass, Plates-Pre compressed Board
	v)	Max. flux density in core steel at rated voltage, frequency and at 90%, 100% and 110% voltage (Tesla)	1.53, 1.7 & 1.87 Tesla respectively
	vi)	Number of limbs of the core	Five
	vii)	Magnetising in rush current	5 to 6 times the rated current

	viii)	No load current at normal tap on and frequency for	
	a)	85% of rated voltage	0.15% Approx.
	b)	100% of rated voltage	0.2% Approx.
	c)	105% of rated voltage	0.3% Approx.
	ix)	Core bolt insulation withstand voltage for one minute (Kv)	2.5 kV

S.No.		PARTICULARS	RATINGS / VALUES
27		Data on windings	
	i)	Maximum current density at CMR and conductor area (A/Sq.mm)	
	a)	HV	<2.7 A/Sq.mm, 168.4 mm2 min.
	b)	IV	<2.7 A/Sq.mm, 137.8 mm2 min.
	c)	LV	<2.7 A/Sq.mm, 392.8 mm2 min.
	ii)	Conductor material	
	a)	HV	
	b)	IV	Electrolytic Grade Copper
	c)	LV	
	iii)	Insulating material used for	
	a)	HV winding	Craft paper covering on conductors and PCB Blocks between Discs, PCB wraps and Spacers between different windings.
	b)	IV winding	
	c)	LV winding	
	iv)	Insulating material used between	
	a)	HV and IV winding	PCB wraps and spacers between different windings
	b)	IV and LV winding	

	c)	LV winding and core	
	v)	Details of special arrangement provided to improve surge voltage distribution in the winding	HV Winding shall be interleaved/countra shielded
	vi)	Whether HV winding inter leaved	HV Winding shall be interleaved/countra shielded
	vii)	Position of the tappings on the winding	Towards the line end of IV Winding i.e., on 220kV side of series winding for achieving +/- 10% of HV variation in steps of 1.25%. It shall be of constant flux voltage variation type
	viii)	Maximum current density under short circuit (A/Sq.mm)	
S.No.		PARTICULARS	RATINGS / VALUES
	a)	HV	24 A/Sq.mm
	b)	IV	24 A/Sq.mm
28		Test Voltages:	HV IV LV Neu.
	i)	Lightning withstand test voltage (kV peak) (HV, IV, LV, Neu.)	1300, 950, 250, 170
	ii)	Power frequency withstand test voltage (kV, rms) (HV, IV, LV, Neu.)	570, 395, 95, 70
	iii)	Switching surge withstand voltage (kV, peak) (HV, IV, LV, Neu.)	1050, --, --, --
29		Partial discharge level at 364 kV (Pico-coulomb)	Less than 500 pc
30	(i)	Noise level when energised at normal voltage and frequency without load (db)	86 db
	(ii)	Governing standard	NEMA TR-1
31		Whether the offered transformer can be transported on railways to destination. YES/NO	Yes
32		COOLING SYSTEM:	
	i)	Name of manufacturer, address & country	
	ii)	Model and type	Manufacturers recommended

S.No.		PARTICULARS	RATINGS / VALUES
	iii)	Number of cooler banks	2 x 50%
	iv)	Number of fan/oil pump per cooler bank	4/2
	v)	Number of standby fan/oil pump	1/1 per cooler bank
	vi)	Rated power input kW (approx.)	Oil pump = 3.7 KW, Fans = 0.7 KW each
	vii)	Capacity (cu.m/min or Lt./min)	Fan = 368 Cu.m/min., Pump = 3400 LPM
	viii)	Rated voltage (volts)	415 Volts
	ix)	Efficiency of motor at full load(%)	80% approx.
	x)	Temp. rise of motor at full load	As per IS-325
	xi)	BHP of driven equipment	Pump = 3.7 Kw, Fan=0.7 KW
	xii)	Degree of Protection (IP)of motor	IP-55
	xiii)	Temp. range over which cooler control is adjustable (deg.C)	40-140 deg.c
	xiv)	Whether the fan and/or pumps are suitable for continuous operation at 85% of their rated voltage	Yes
	xv)	Calculated time constant in hours	
	a)	Natural cooling	4 hours
	b)	Forced air cooling	2 hours
33		On Load Tap Changing gear (OLTC)	
	i)	Name of manufacturer, address and country	
	ii)	Model and type	High Speed resister Type
	iii)	Class as per IEC 60214 and corresponding rated insulation levels	220kV Class
	iv)	Rated current (Amps)	800 amp
	v)	Rated voltage (kV)	220kV Class
	vi)	Number of steps	16
	vii)	Step voltage (kV)	2.888 kV
	viii)	Whether control suitable for	
	a)	Remote/local operation	Yes
	b)	Auto/manual operation	Yes
	c)	Parallel operation	Yes
	ix)	Rated voltage & frequency of drive motor(volts & Hz) and permissible variation	415 V 50 HZ 3 Phase

	x)	Rated voltage of protective control devices (volts)	110 V AC
	xi)	Particulars of protective devices provided (Over current/over run/Restarting device)	Oil Surge Relay
	xii)	Whether the control panel complete with OLTC control equipment for installation in the Control room included in the scope of supply at no extra cost YES/NO	Yes
	xiii)	Time taken to change one step(sec.)	5 sec Approx.
	xiv)	Temperature of tap-changer eNeu.ironment Minimum/Maximum	suitable for entire range of oil temperature
S.No.		PARTICULARS	RATINGS / VALUES
33	xv)	Temperature of motor-drive mechanism environment	-5 deg.C to 50 deg.C
	xvi)	Rated characteristics	
	a)	Rated through current (Amp)	505.2 amp (actual current of HV at full load & at min. tap)
	b)	Maximum rated through current (A)	800 amp (rated current of OLTC)
	c)	Rated step voltage (kV)	2.888 kV
	d)	Maximum rated step voltage (kV)	3.5 kV
	e)	Rated frequency (Hz)	50 HZ
	f)	Rated insulation level	245 kV Class (460 kV rms BIL: 1050 kVp)
	xvii)	Relevant rated step voltage (kV) (Rated step voltage corresponding to specific rated through current)	2.888 kV at 505.2 amp
	xviii)	Oil compartments for divertor switches & selector switches	
	a)	Pressure withstand rating	15 PSi
	b)	Vaccum withstand rating	Full
	xix)	Details of protective services against increase of pressure provided	
	a)	Oil flow controlled relay Yes/No	Yes

	b)	Over pressure relay Yes/No	No
	c)	Pressure relief devices Yes/No	No
	xx)	Details of limiting devices for protection of OLTC against transient over voltages and any limitation imposed during tests on completed transformers	No limitation on Transformer testing
	xxi)	Temperature rise of contacts & corresponding contact material in air/oil	Less than 20 deg C/ contact material as per supplier's std.
	xxii)	Transition impedance type & value	Resistor type / will furnish later

S.No.		PARTICULARS	RATINGS / VALUES
33	xxiii)	No. of operations corresponding to maximum rated through current and relevant rated step voltage	2,00,000
	xxiv)	Whether copies of type tests performed on OLTC enclosed YES/NO	Yes
	xxv)	Partial discharge (micro columbs at ----- kV)	NA
	xxvi)	Details of oil purification and filteration plant	
	a)	Manufacturer, address & country	
	b)	Model	As per supplier’s recommendations
	c)	Capacity	60 litres per min
	d)	Governing standard.	Supplier’s std.
34		BUSHINGS: (HV, IV, LV)	HV IV LV Neu.
	i)	Model and type	Condenser Bushing <-oil communicating type--
	ii)	Rated current (Amps)	1250 1250 3150 2000
	iii)	Lightning impulse withstand voltage(HV,IV,Neutral and LV)	1425 1050 250 170
		(kV Peak)	
	iv)	Switching surge withstand voltage (kV Peak)	1050 -- -- --
	v)	Power frequency withstand voltage	

		a) Wet for one minute (kV rms)	630 460 95 75
		b) Dry for one minute (kV rms)	630 460 95 75
	vi)	Visible carona discharge voltage (kV rms)	320 175 -- --
	vii)	Partial discharge level at 364 kV	≤ 10 pC for HV, IV & LV
		(Pico-coulomb)	-
	viii)	Creapage distance in air (mm)	10500 6125 1300 900
	ix)	Quality of oil in bushing and specification of oil used lits.)	200, 55 ltrs apprx. (EHV Grade oil)
	x)	Weight of assembled bushing (kg)	1000 450 50

S.No.		PARTICULARS	RATINGS / VALUES
	xi)	Free space required above the transformer tank top for removal of bank (meters)	8 meters
	xii)	Whether terminal connectors for all bushings included in the scope of supply (YES/NO)	Yes
	xiii)	Are bushing dimensions as per specification (YES/NO)	Yes
	xiv)	Whether test tap provided or not (YES/NO)	Yes Yes NA
35		CONSERVATOR:	
	i)	Total volume (liters)	6500 lits.
	ii)	Volume between the highest and lowest visible oil levels (lts.)	5600 lits.
	iii) a)	Material of air cell	Nitrile/Neoprne/Hyplon
	b)	Literature on air cell enclosed YES/NO	Yes
	iv)	Continuous temp. withstand capacity of air cell	100 deg. C
36		Tank:	
	i)	Material and thickness of plate for tank construction	Mild Steel
			Side = 10mm, Bottom=50 mm, Top Cover = 20 mm Approx.
	ii)	Tank cover conventional or bell type	Bell type

	iii)	No. of pressure relief devices provided	2
	iv)	Operating pressure of relief device	8 psi approx.
	v)	Vaccum withstand capacity of	
	a)	Main tank	Full
	b)	Radiators and accesssories	Full
	vi)	Pressure withstand capacity of	
	a)	Main tank	Continuous internal Pressure of 100 kN/sqm over normal hydrostatic pressure of oil

S.No.		PARTICULARS	RATINGS / VALUES
	b)	Radiators and accesssories	
	vii)	Whether the impact recorder provided	Yes
	viii)	Permissible limits of displacement during transit	Impact recorder shall be fitted during Transport.
	ix)	Confirm whether impact recorder fitted during Transit Yes/No	Yes
37		Bushing type current transformers:	
	i)	Voltage class	As per Specification
	ii)	No. of cores	As per Specification
	iii)	Ratio	
	iv)	Accuracy class	
	v)	Burden	
	vi)	Accuracy limit factor	As per Specification
	vii)	Maximum resistance of secondary winding (ohms)	As per Specification
	viii)	Knee point voltage (volts)	
	ix)	Current rating of secondaries(Amps)	
38		Insulating OIL	
	i)	Name of Manufacturer, address & country	
	ii)	Governing Standard	IS-335
	a)	Quantity of oil Before Filling Before Commissioning	75 KL including 10% extra

	b)	Parameter of insulating oil Before Filling Before Commissioning	
			Before Filling ‘ Before commissioning
		i) Moisture content (PPm)	15 10
		ii) Tan delta at 90 deg.C	0.002 0.05
		iii) Resistivity (Ohm-cm)	35 X 10 12 1x10 2
		iv) Breakdown strength (kV)	30 kV 60 kV
		v) Interfacial tension at 20 deg.C	0.04 N/m 0.03 N/m

S.No.		PARTICULARS	RATINGS / VALUES
39		Temperature indicators - Range & Accuracy	
	i)	OTI	0 to 150 deg. C +-1.5%
	ii)	WTI	o to 150 deg. C +-1.5%
	iii)	RWTI	o to 150 deg. C +-1.5%
40		Minimum clearances(mm)	
	i)	In oil	HV IV LV
		- Between phase to phase	Adequate with respect to shape of electrode and Voltage Class
		- Between phase to ground	
	ii)	In Air	HV IV LV
	a)	- Between phase to phase	4000, 2000, 530
	b)	- Between phase to ground	3500, 1820, 480
41		WEIGHTS AND DIMENSIONS:	
	i)	Weights (kg)	Approx.
	a)	Core	73500
	b)	Windings	38000
	c)	Tank	25000
	d)	Fittings	40000
	e)	Oil	60000
	f)	Total weights of complete transformer with oil and fittings	240000

	ii)	Dimensions (meters)	Approx.
	a)	Overall height above track	9.15
	b)	Overall length	17.3
	c)	Overall breadth	12.6
	d)	Minimum bay width required for installation of the transformer	
	iii)	Weight of the heaviest package of the transformer arranged for transportation	150 Tonnes
42	A)	LIFTING JACKS:	
	i)	Number of jacks included in one set	6
	ii)	Type and make	Hydraulic, Make XYZ
S.No.		PARTICULARS	RATINGS / VALUES
	iii)	Capacity	80 Tonnes
	iv)	Pitch	150 mm
	v)	Lift	470 mm
	vi)	Height in close position	320 mm
	B)	RAIL TRACK GUAGES:	
	i)	3 rails or 4 rails	4 Nos.
	ii)	Distance between adjacent rails on shorter axis	1676 mm
	iii)	Distance between adjacent rails on longer axis	1676 mm