A short Course on

Electrical Power Transformer

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Electrical Power Transformer

Definition of Transformer

A transformer is a static machine used for transforming power from one circuit to another without changing frequency. This is very basic definition of transformer.

Electrical Power Transformer
Working Principle of Transformer
Ideal Transformer
Theory of Transformer
EMF Equation of Transformer
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Over Fluxing in Transformer
Three phase transformer
Current Transformer
Voltage Transformer
Accuracy Limit & Instrument Security Factor
Knee Point Voltage of Current Transformer
Earthing or Grounding Transformer
External & Internal Faults in Transformer
Backup Protection of Transformer
Differential Protection of Transformer
Restricted Earth Fault Protection
Buchholz Relay in Transformer
Transformer Testing
History of Transformer

The History of transformer commenced in the year of 1880. In the year of 1950 400KV electrical power transformer first introduced in high voltage electrical power system. In the early 1970s unit rating as large as 1100MVA were produced and 800KV and even higher KV class transformers were manufactured in year of 1980.

Use of Power Transformer

Generation of Electrical Power in low voltage level is very much cost effective. Hence Electrical Power are generated in low voltage level. Theoretically, this low voltage leveled power can be transmitted to the receiving end. But if the voltage level of a power is increased, the current of the power is reduced which causes reduction in ohmic or I^2R losses in the system, reduction in cross sectional area of the conductor i.e. reduction in capital cost of the system and it also improves the voltage regulation of the system. Because of these, low leveled power must be stepped up for efficient electrical power transmission. This is done by step up transformer at the sending side of the power system network. As this high voltage power may not be distributed to the consumers directly, this must be stepped down to the desired level at the receiving end with help of step down transformer. These are the use of electrical power transformer in the Electrical Power System.

Two winding transformers are generally used where ratio between High Voltage and Low Voltage is greater than 2. It is cost effective to use Auto transformer where the ratio between High Voltage and Low Voltage is less than 2. Again Three Phase Single Unit Transformer is more cost effective than a bank of three Single Phase Transformer unit in a three phase system. But still it is preferable to use later where power dealing is very large since such large size of Three Phase Single Unit Power Transformer may not be easily transported from manufacturer's place to work site.

Types of Transformer

Transformers can be categorized in different ways, depending upon their purpose, use, construction etc. The types of transformer are as follows,

• Step Up Transformer & Step Down Transformer - Generally used for stepping up and down the voltage level of power in transmission and distribution power network.
• **Three Phase Transformer** & Single Phase Transformer - Former is generally used in three phase power system as it is cost effective than later but when size matters it is preferable to use **bank of three Single Phase Transformer** as it is easier to transport three single phase unit separately than one single three phase unit.

• Electrical Power Transformer, Distribution Transformer & Instrument Transformer - Transformer generally used in transmission network is normally known as Power Transformer, distribution transformer is used in distribution network and this is lower rating transformer and **current transformer & potential transformer**, we use for relay and protection purpose in **electrical power system** and in different instruments in industries are called **Instrument Transformer**.

• **Two Winding Transformer** & **Auto Transformer** - Former is generally used where ratio between High Voltage and Low Voltage is greater than 2. It is cost effective to use later where the ratio between High Voltage and Low Voltage is less than 2.

• Outdoor Transformer & Indoor Transformer - Transformers designed for installing at outdoor is Outdoor Transformer and Transformers designed for installing at indoor is Indoor Transformer
What is Transformer?

Definition of Transformer

Electrical Power Transformer is a static device which transforms electrical energy from one circuit to another without any direct electrical connection and with the help of mutual induction between to windings. It transforms power from one circuit to another without changing its frequency but may be in different voltage level. This is very short and simple definition of transformer, as we will go through this portion of tutorial related to Electrical Power Transformer, we will understand more clearly and deeply "what is Transformer ?" and basic theory of transformer.

Working Principle of transformer

The working principle of transformer is very simple. It depends upon Faraday's laws of Electromagnetic Induction. Actually mutual induction between two or more winding is responsible for transformation action in an electrical transformer.

Faraday's laws of Electromagnetic Induction

According to these Faraday's laws, "Rate of change of flux linkage with respect to time is directly proportional to the induced EMF in a conductor or coil".

Basic Theory of Transformer

Say you have one winding which is supplied by an alternating electrical source. The alternating current through the winding produces a continually changing flux or alternating flux surrounds the winding. If any other winding is brought nearer to the previous one, obviously some portion of this flux will link with the second. As this flux is continually changing in its amplitude and direction, there must be a change in flux linkage in the second winding or coil. According to Faraday's laws of Electromagnetic Induction, there must be an EMF induced in the second. If the circuit of the latter winding is closed, there must be a current flows through it. This is the simplest form of electrical power transformer and this is most basic of working principle of transformer.
The winding which takes electrical power from the source, is generally known as Primary Winding of transformer. Here it is first winding. The winding which gives the desired output voltage due to mutual induction in the transformer, is commonly known as Secondary Winding of Transformer. Here it is second winding.

The above mentioned form of transformer is theoretically possible but not practically, because in open air very tiny portion of the flux of the first winding will link with second so the current flows through the closed circuit of latter, will be so small that it may be difficult to measure.

The rate of change of flux linkage depends upon the amount of linked flux, with the second winding. So it desired to be linked almost all flux of primary winding, to the secondary winding. This is effectively and efficiently done by placing one
low reluctance path common to both the winding. This low reluctance path is core of transformer, through which maximum number of flux produced by the primary is passed through and linked with the secondary winding. This is most basic theory of transformer.

**Main constructional parts of transformer**

So three main parts of a transformer are,

1. Primary Winding of transformer - which produces magnetic flux when it is connected to electrical source.
2. Magnetic Core of transformer - the magnetic flux produced by the primary winding, will pass through this low reluctance path linked with secondary winding and creates a closed magnetic circuit.
3. Secondary Winding of transformer - the flux, produced by primary winding, passes through the core, will link with the secondary winding. This winding is also wound on the same core and gives the desired output of the transformer.
Ideal Transformer

Definition of Ideal Transformer

An *Ideal Transformer* is an imaginary transformer which does not have any loss in it, means no core losses, copper losses and any other *losses in transformer*. Efficiency of this transformer is considered as 100%.

Ideal Transformer Model

*Ideal Transformer Model* is developed by considering a transformer which does not have any loss. That means the windings of the transformer are purely inductive and *core of transformer* is loss free. There is zero *Leakage Reactance of Transformer*. As we said, whenever we place a low reluctance core inside the windings, maximum amount of flux passes through this core; but still there is some flux which does not pass through the core but passes through the insulation used in the transformer. This flux does not take part in the transformation action of the transformer. This flux is called *leakage flux of transformer*. In an *Ideal Transformer*, this leakage flux is considered also nil. That means 100% flux passes through the core and linked with both primary and secondary windings of transformer. Although every winding is desired to be purely inductive but it has some resistance in it which causes voltage drop and $I^2R$ loss in it. In such **ideal transformer model**, the winding are also considered, ideal that means resistance of the winding is zero.
Now if an alternating source voltage $V_1$ is applied in the primary winding of that Ideal Transformer, there will be a counter self emf $E_1$ induced in the primary winding which is purely $180^\circ$ in phase opposition with supply voltage $V_1$.

For developing counter emf $E_1$ across the primary winding it draws current from the source to produces required magnetizing flux. As the primary winding is purely inductive, that current is in $90^\circ$ lags from the supply voltage. This current is called magnetizing current of transformer $I_\mu$.

This alternating current, $I_\mu$, produces an alternating magnetizing flux $\Phi$ which is proportional to that current and hence in phase with it. As this flux is also linked with secondary winding through the core of transformer, there will be another emf.
E₂ induced in the secondary winding, this is mutually induced emf. As the secondary is placed on the same core where the primary winding is placed, the emf induced in the secondary winding of transformer, E₂ is in the phase with primary emf E₁ and in phase opposition with source voltage V₁.

The above chapter was about a brief discussion about ideal transformer it has also explained the basic ideal transformer model.
Theory of Transformer

We have discussed about theory of Ideal Transformer for better understanding of actual elementary theory of transformer. Now we will go through one by one practical aspects of an electrical power transformer and try to draw vector diagram of transformer in every step. As we said that in ideal transformer there are no core losses in transformer i.e. loss free core of transformer. But in practical transformer there are hysteresis and eddy current losses in transformer core.

Theory of transformer on no-load, and having no winding resistance and no leakage reactance of transformer

Let us consider one electrical transformer with only core losses. That means it has only core losses but no copper lose and no leakage reactance of transformer. When an alternating source is applied in the primary, the source will supply the current for magnetizing the core of transformer.

But this current is not the actual magnetizing current, little bit greater than actual magnetizing current. Actually total current supplied from the source has two components one is magnetizing current which is merely utilized for magnetizing the core and other component of the source current, is consumed for compensating the core losses in transformer.

Because of this core loss component, the source current in transformer on no-load condition, supplied from the source as source current is not exactly at 90° lags of supply voltage but it lags behind an angle θ is less than 90°.

If total current supplied from source is $I_0$, it will have one component in phase with supply voltage $V_1$ and this component of the current $I_w$ is core loss component. This component is taken in phase with source voltage, because it is associated with active or working losses in transformer. Other component of the source current is denoted as $I_μ$. This component produces the alternating magnetic flux in the core, so it is watt-less means it is reactive part of the transformer source current. Hence $I_μ$ will be in quadrature with $V_1$ and in phase with alternating flux $Φ$.

Hence, total primary current in transformer on no-load condition can be represented as

$$I_0 = I_μ + I_w$$

and,

$$|I_μ| = |I_0| \cos \theta$$
\[ |I_w| = |I_o| \sin \theta \]
\[ |I_o| = (|I_u|^2 + |I_w|^2)^{\frac{1}{2}} \]

Now you have seen how simple to explain the theory of transformer in no-load.

**Theory of transformer on load but having no winding resistance and leakage reactance**

Now we will examine the behavior of above said transformer on load, that means load is connected to the secondary terminals. Consider, transformer having core loss but no copper loss and leakage reactance. Whenever load is connected to the secondary winding, load current will start to flow through the load as well as secondary winding. This load current solely depends upon the characteristics of the load and also upon upon secondary voltage of the transformer. This current is called secondary current or load current, here it is denoted as \( I_2 \). As \( I_2 \) is flowing through the secondary, a self mmf in secondary winding will be produced. Here it is \( N_2 I_2 \), where, \( N_2 \) is the number of turns of the secondary winding of transformer.
This mmf or magneto motive force in the secondary winding produces flux $\varphi_2$. This $\varphi_2$ will oppose the main magnetizing flux and momentarily weakens the main flux and tries to reduce primary self induced emf $E_1$.

If $E_1$ falls down below the primary source voltage $V_1$, there will be an extra current flows from source to primary winding. This extra primary current $I_2'$ produces extra flux $\varphi'$ in the core which will neutralized the secondary counter flux $\varphi_2$. Hence the main magnetizing flux of core, $\Phi$ remain unchanged irrespective of load.

So total current, this transformer draws from source can be divided into two components, first one is utilized for magnetizing the core and compensate the core loss i.e. $I_o$. It is, no-load component of the primary current. Second one is utilized for compensating the counter flux of the secondary winding. It is known as load component of the primary current. Hence total no load primary current $I_1$ of a transformer having no winding resistance and leakage reactance can be represented as follows

$$I_1 = I_o \oplus I_2'$$

Where $\theta_2$ is the angle between Secondary Voltage and Secondary Current of transformer. Now we will proceed one further step toward more practical aspect of a transformer.
Theory of transformer on load, with resistive winding, but no leakage reactance

Now, consider the winding resistance of transformer but no leakage reactance. So far we have discussed about the transformer which has ideal windings means winding with no resistance and leakage reactance, but now we will consider one transformer which has internal resistance in the winding but no leakage reactance. As the windings are resistive, there would be a voltage drop in the windings.

We have proved earlier that total primary current from the source on load is $I_1$. The voltage drop in the primary winding with resistance, $R_1$ is $I_1R_1$. Obviously induced emf across primary winding $E_1$, is not exactly equal to source voltage $V_1$. $E_1$ is less than $V_1$ by voltage drop $I_1R_1$.

$$V_1 = E_1 + I_1R_1$$

Again in the case of secondary, the voltage induced across the secondary winding, $E_2$ does not totally appear across the load since it also drops by an amount $I_2R_2$, where $R_2$ is the secondary winding resistance and $I_2$ is secondary current or load current.

Similarly voltage equation of the secondary side of the transformer will be

$$V_2 = E_2 - I_2R_2$$
Theory of transformer on load, with resistance as well as leakage reactance in transformer windings

Now we will consider the condition, when there is leakage reactance of transformer as well as winding resistance of transformer.

Let leakage reactances of primary and secondary windings of the transformer are $X_1$ and $X_2$ respectively.

Hence total impedance of primary and secondary winding with resistance $R_1$ and $R_2$ respectively, can be represented as,

$$Z_1 = R_1 + jX_1 \text{ (impedance of primary winding)}$$

$$Z_2 = R_2 + jX_2 \text{ (impedance of secondary winding)}$$

We have already established the voltage equation of a transformer on load, with only resistances in the windings; where voltage drops in the windings occur only due to resistive voltage drop. But when we consider leakage reactances of transformer windings, voltage drop occurs in the winding not only because of resistance, it is because of impedance of transformer windings. Hence, actual voltage equation of a transformer can easily be determined by just replacing resistances $R_1$ & $R_2$ in the previously established voltage equations by $Z_1$ and $Z_2$.

Therefore, the voltage equations are,

$$V_1 = E_1 + I_1Z_1 \text{ & } V_2 = E_2 - I_2Z_2$$
\[ V_1 = E_1 + I_1(R_1 + jX_1) \Rightarrow V_1 = E_1 + I_1R_1 + jI_1X_1 \]

\[ V_2 = E_2 - I_2(R_2 + jX_2) \Rightarrow V_2 = E_2 - I_2R_2 - jI_2X_2 \]

Resistance drops are in the direction of current vector but reactive drop will be in perpendicular to the current vector as shown in the above vector diagram of transformer.
**EMF equation of Transformer**

**EMF Equation of transformer** can be established in very easy way. Actually in *electrical power transformer*, one alternating electrical source is applied to the primary winding and due to this, magnetizing current flows through the primary which produces alternating flux in the core of transformer. This flux likes with both primary and secondary windings. As this flux is alternating in nature there must be a rate of change of flux. According to Faraday’s law of electromagnetic induction if any coil or conductor links with any changing flux, there must be an induced emf in it. As the current source to primary, is sinusoidal, the flux induced by it will be also sinusoidal. Hence the function of flux may be considered as a sine function. Mathematically derivative of that function will give a function for rate of change of flux linkage with respect to time. This later function will be a cosine function since \( \frac{d}{dt}(\sin \theta) = \cos \theta \). So if we derive the expression for rms value of this cosine wave and multiply it with number of turns of the winding we will easily get the expression for rms value of induced emf of that winding. In this way we can easily derive the *emf equation of transformer*.

![Diagram of Transformer](image)

Let, \( T \) is number of turns in a winding,
\( \Phi_m \) is the maximum flux in the core in Wb.

As per Faraday's laws of electromagnetic Induction,
emf, \( e = -T \cdot \frac{d\phi}{dt} \)

Where \( \phi \) is the instantaneous alternating flux and represented as,

\( \phi = \Phi_m \sin 2\pi ft \)

Hence, \( e = \frac{d(\Phi_m \sin 2\pi ft)}{dt} \)

\[ \Rightarrow e = -T\Phi_m \cos 2\pi ft \times 2\pi f \]

\[ \Rightarrow e = -T\Phi_m 2\pi f \cos 2\pi ft \]

As the maximum value of \( \cos 2\pi ft \) is 1, the maximum value of induced emf \( e \) is,

\( e_m = T \Phi_m^2 \pi f \)

To obtain the rms value of induced counter emf, divide this maximum value of \( e \) by \( \sqrt{2} \).

Then, \( E = \frac{2\pi}{\sqrt{2}} \times \Phi_m f T \) Volts

\[ \Rightarrow E = 4.44\Phi_m f T \text{ Volts} \quad \text{(Since,} \frac{2\pi}{\sqrt{2}} = 4.44) \]

This is EMF equation of transformer

If \( E_1 \) & \( E_2 \) are primary and secondary emfs and \( T_1 \) & \( T_2 \) are primary and secondary emfs then, voltage ratio or turns ratio of transformer is,

\[ \frac{E_1}{E_2} = \frac{4.44\Phi_m f T_1}{4.44\Phi_m f T_2} = \frac{T_1}{T_2} \]

\[ \Rightarrow \frac{E_1}{E_2} = \frac{T_1}{T_2} \]

**Transformation Ratio of Transformer**

This constant is called transformation ratio of transformer, if \( T_2 > T_1, \ K > 1 \), then the transformer is step up transformer. If \( T_2 < T_1, \ K < 1 \), then the transformer is step down transformer.

**Voltage Ratio of Transformer**

This above said ratio is also known as voltage ratio of transformer if it is expressed as ratio of the primary and secondary voltages of transformer.
Turns Ratio of Transformer

As the voltages in primary and secondary of transformer is directly proportional to number of turns in the respective winding, the transformation ratio of transformer is sometime expressed in ratio of turns and referred as **turns ratio of transformer**

Resistance and Leakage Reactance of Transformer or Impedance of Transformer

Leakage Reactance of Transformer

All the flux in transformer will not be able to link with both the primary and secondary windings. A small portion of flux will link either winding but not both. This portion of flux is called leakage flux. Due to this **leakage flux in transformer** there will be a self - reactance in the concerned winding. This self-reactance of transformer is alternatively known as **leakage reactance of transformer**. This self - reactance associated with **resistance of transformer** is impedance. Due to this **impedance of transformer** there will be voltage drops in both primary and secondary transformer windings.

Resistance of Transformer

Generally both primary and secondary windings of **electrical power transformer** are made of copper. Copper is very good conductor of current but not a super conductor. Actually super conductor and super conductivity both are conceptual, practically they are not available. So both windings will have some resistance. This internal resistance of both primary and secondary windings are collectively known as **resistance of transformer**.

Impedance of Transformer

As we said, both primary and secondary windings will have resistance and leakage reactance. These resistance and reactance will be in combination is nothing but **impedance of transformer**. If $R_1$ & $R_2$ and $X_1$ & $X_2$ are primary & secondary resistance & leakage reactance of transformer respectively, then $Z_1$ & $Z_2$ impedance of primary & secondary windings are respectively ,

$$Z_1 = R_1 + jX_1$$

$$Z_2 = R_2 + jX_2$$
The impedance of a transformer plays a vital role during parallel operation of transformer.

**Leakage Flux in Transformer**

In an *ideal transformer* all the flux will link with both primary and secondary windings, but in reality it is impossible to link all the flux in the transformer with both primary and secondary windings. Although maximum flux will link with both windings through the core of the transformer but still there will be a small amount of flux which will link either winding not both. This flux is called leakage flux which will pass through the winding insulation and transformer insulating oil instead of passing through the core. Due to this *leakage flux in transformer*, both primary and secondary winding have leakage reactance. These reactance of transformer is nothing but *leakage reactance of transformer*. This phenomena in transformer is known as Magnetic Leakage.

**Voltage drops in the windings occur due to impedance of transformer.** Impedance is combination of resistance and leakage reactance of transformer. If we apply voltage $V_1$ across primary of transformer, there will be a component $I_1X_1$ to balance primary self induced emf due to primary leakage reactance. (Here, $X_1$ is primary leakage reactance). Now if we also consider voltage drop due to primary resistance of transformer, then voltage equation of a transformer can easily be written as,

$$V_1 = E_1 + I_1R_1 + jI_1X_1$$

Similarly for secondary leakage reactance, the voltage equation of secondary side is,
\[ V_2 = E_2 - I_2(R_2 + jX_2) \implies V_2 = E_2 - I_2R_2 - jI_2X_2 \]

Here in the figure above, the primary and secondary windings are shown in separate limbs and this arrangement could result a large leakage flux in transformer as because there is a big room for leakage. Leakage in primary and secondary could be eliminated if the windings could be made to occupy the same space. This of course is physically impossible but by placing secondary and primary in concentric manner can solve the problem in good extent.
Equivalent Circuit of Transformer

Equivalent impedance of Transformer is essential to be calculated as because the electrical power transformer is an electrical power system equipment so for estimating different parameters of electrical power system it may be required to calculate total internal impedance of an electrical power transformer viewing from primary side or secondary side as per requirement. This calculation requires equivalent circuit of transformer referred to primary or equivalent circuit of transformer referred to secondary sides respectively. Percentage impedance is also very essential parameter of transformer. Special attention is to be given to this parameter during installing a transformer in an existing electrical power system. Percentage impedance of different power transformers should be properly matched during parallel operation of these transformers. The percentage impedance can be derived from equivalent impedance of transformer so it can be said that equivalent circuit of transformer is also required during calculation of % impedance.

Equivalent Circuit of Transformer referred to Primary

For drawing equivalent circuit of transformer referred to primary, first we have to establish general equivalent circuit of transformer then we will modify it for referring from primary side. For doing this we first recall the complete vector diagram of a transformer which is shown in the figure below.

Let us consider the transformation ratio be,
\[ K = \frac{N_1}{N_2} = \frac{E_1}{E_2} \]
In the figure right, the applied voltage to the primary is \( V_1 \) and voltage across the primary winding is \( E_1 \). Total current supplied to primary is \( I_1 \). So the voltage \( V_1 \) applied to the primary, is partly dropped by \( I_1Z_1 \) or \( I_1R_1 + jI_1X_1 \) before it appears across primary winding. The voltage appeared across winding is countered by primary induced emf \( E_1 \). So voltage equation of this portion of the transformer can be written as

\[
V_1 - (I_1R_1 + jI_1X_1) = E_1
\]

The equivalent circuit for that equation can be drawn as below,

From the vector diagram above it is found that total primary current \( I_1 \) has two components one is no-load component \( I_0 \) and other is load component \( I_2' \). As this primary current has two components or branches so there must be a parallel path with primary winding of transformer. This parallel path of current is known as excitation branch of equivalent circuit of transformer. The resistive and reactive branches of the excitation circuit can be represented as

\[
R_o = E_1 / I_w \quad \text{and} \quad X_o = E_1 / I_\mu.
\]

The load component \( I_2' \) flows through the primary winding of transformer and induced voltage across the winding is \( E_1 \) as shown in the figure right. This induced voltage \( E_1 \) transforms to secondary and it is \( E_2 \) and load component of primary current \( I_2' \) is transformed to secondary as secondary current \( I_2 \). Current of secondary is \( I_2 \). So the voltage \( E_2 \) across secondary winding, is partly dropped by \( I_2Z_2 \) or \( I_2R_2 + jI_2X_2 \) before it appears across load. The load voltage is \( V_2 \).
The complete equivalent circuit of transformer is shown below.

Now if we see the voltage drop in secondary from primary side then it would be 'K' times greater and would be written as $K.Z_2.I_2$.
Again $I_2'.N_1 = I_2.N_2$
$\Rightarrow I_2 = I_2'.N_1 / N_2$
$\Rightarrow I_2 = K.I_2'$
Therefore,
$K.Z_2.I_2 = K.Z_2.K.I_2'$
$= K^2.Z_2.I_2'$
From above equation,
Secondary impedance of transformer referred to primary is, $Z_2' = K^2.Z_2$
Hence, $R_2' = K^2.R_2$
and $X_2' = K^2.X_2$
So The complete equivalent circuit of transformer referred to primary is shown in
the figure below,

Approximate Equivalent Circuit of Transformer

Since $I_o$ is very small compared to $I_1$, it is less than 5% of full load primary current, $I_o$ changes the voltage drop insignificantly. Hence, it is good approximation to ignore the excitation circuit in approximate equivalent circuit of transformer. The winding resistance and reactance being in series can now be combined into equivalent resistance and reactance of transformer referred to any particular side. In this case it is side 1 or primary side. Here $V_2' = K.V_2$

Approximate equivalent circuit of transformer referred to primary
Equivalent Circuit of Transformer referred to Secondary

In similar way approximate equivalent circuit of transformer referred to secondary can be drawn.
Where, equivalent impedance of transformer referred to secondary, can be derived as
\[ Z_1' = \frac{Z_1}{K^2} \]
Therefore,
\[ R_1' = \frac{R_1}{K^2} \text{ and } \]
\[ X_1' = \frac{X_1}{K^2} \]
Here, \[ V_1' = \frac{V_1}{K} \]

\[
\begin{align*}
I_2 & \quad X_{eq} = X_1' + X_2 \quad R_{eq} = R_1' + R_2 \\
V_1' & \quad Z_{eq} = Z_1' + Z_2 \quad V_2
\end{align*}
\]

Approximate equivalent circuit of transformer referred to secondary
Voltage Regulation of Transformer

What is Voltage Regulation?

Definition

The voltage regulation is the percentage of voltage difference between no load and full load voltages of a transformer with respect to its full load voltage.

Explanation of Voltage Regulation of Transformer

Say a electrical power transformer is open circuited means load is not connected with secondary terminals. In this situation the secondary terminal voltage of the transformer will be its secondary induced emf $E_2$. Whenever full load is connected to the secondary terminals of the transformer, rated current $I_2$ flows through the secondary circuit and voltage drops comes into picture. At this situation, primary winding will also draw equivalent full load current from source. The voltage drop in the secondary is $I_2Z_2$ where $Z_2$ is the secondary impedance of transformer. If now, at this loading condition any one measures the voltage between secondary terminals, he or she will get voltage $V_2$ across load terminals which is obviously less than no load secondary voltage $E_2$ and this is because of $I_2Z_2$ voltage drop in the transformer.

Expression of Voltage Regulation of transformer

Expression of Voltage Regulation of Transformer, represented in percentage, is

Voltage regulation (%) = $\frac{(E_2 - V_2)}{V_2} \times 100$

Voltage Regulation of Transformer for lagging Power Factor

Now we will derive the expression of voltage regulation in detail, say lagging Power Factor of the load is $\cos \theta_2$, that means angle between secondary current and voltage is $\theta_2$

Here, from the above diagram,

$OC = OA + AB + BC$

Here, $OA = V_2$

Here, $AB = AE \cos \theta_2 = I_2R_2 \cos \theta_2$
and, BC = DEsinθ₂ = I₂X₂sinθ₂

Voltage Regulation at Lagging Power Factor

Angle between OC & OD may be very small so it can be neglected and OD is considered nearly equal to OC i.e.

E₂ = OC = OA &plus; AB &plus; BC

E₂ = OC = V₂ &plus; I₂R₂cosθ₂ &plus; I₂X₂sinθ₂ ..................1

Voltage Regulation of transformer at lagging power factor,

Voltage Regulation (%) = \((E₂ - V₂)/ V₂ \times 100\% = ((I₂R₂cosθ₂ &plus; I₂X₂sinθ₂)/ V₂) \times 100\% \)

Voltage Regulation of Transformer for Leading Power Factor

Let's derive the expression of voltage regulation with leading current, say leading Power Factor of the load is cosθ₂, that means angle between secondary current and voltage is θ₂
Here, from the above diagram,

\[ OC = OA + AB - BC \]

Here, \( OA = V_2 \)

Here, \( AB = AE \cos \theta_2 = I_2 R_2 \cos \theta_2 \)

and, \( BC = DE \sin \theta_2 = I_2 X_2 \sin \theta_2 \)

Angle between \( OC \) & \( OD \) may be very small so it can be neglected and \( OD \) is considered nearly equal to \( OC \) i.e.

\[ E_2 = OC = OA + AB - BC \]

\[ E_2 = OC = V_2 + I_2 R_2 \cos \theta_2 - I_2 X_2 \sin \theta_2 \] ..........................2

**Voltage Regulation of transformer** at leading power factor,

Voltage Regulation (%) = \( \frac{(E_2 - V_2)}{V_2} \times 100\% = \frac{(I_2 R_2 \cos \theta_2 - I_2 X_2 \sin \theta_2)}{V_2} \times 100\% \)
Losses in Transformer

As the electrical transformer is a static device, mechanical loss in transformer normally does not come into picture. We generally consider only electrical losses in transformer. Loss in any machine is broadly defined as difference between input power and output power.

When input power is supplied to the primary of transformer, some portion of that power is used to compensate core losses in transformer i.e. Hysteresis loss in transformer and Eddy Current loss in transformer core and some portion of the input power is lost as $I^2R$ loss and dissipated as heat in the primary and secondary winding, as because these windings have some internal resistance in them. The first one is called core loss or iron loss in transformer and later is known as ohmic loss or copper loss in transformer. Another loss occurs in transformer, known as Stray Loss, due to Stray fluxes link with the mechanical structure and winding conductors.

Copper loss in transformer

Copper loss is $I^2R$ loss, in primary side it is $I_1^2R_1$ and in secondary side it is $I_2^2R_2$ loss, where $I_1$ & $I_2$ are primary & secondary current of transformer and $R_1$ & $R_2$ are resistances of primary & secondary winding. As the both primary & secondary currents depend upon load of transformer, so copper loss in transformer vary with load.

Core losses in transformer

Hysteresis loss and eddy current loss, both depend upon magnetic properties of the materials used to construct the core of transformer and its design. So these losses in transformer are fixed and do not depend upon the load current. So core losses in transformer which is alternatively known as iron loss in transformer and can be considered as constant for all range of load.

Hysteresis loss in transformer is denoted as,

$$W_h = K_h f B_m^{1.6} \text{ watts}$$

Eddy Current loss in transformer is denoted as,

$$W_e = K_e f^2 k_f^2 B_m^2 \text{ watts}$$

Where, $K_h$ = Hysteresis Constant.

$K_e$ = Eddy Current Constant.
K_f = form Constant.

Copper loss can simply be denoted as,

\[ I_L^2R_2' + \text{Stray loss} \]

Where, \( I_L = I_2 \) = load of transformer, and \( R_2' \) is the resistance of transformer referred to secondary.

Now we will discuss Hysteresis loss and Eddy Current loss in little bit more details for better understanding the topic of losses in transformer

**Hysteresis loss in transformer**

Hysteresis loss in transformer can be explained in different ways. We will discuss two of them, one is physical explanation other is mathematical explanation.

**Physical explanation of Hysteresis loss**

The magnetic core of transformer is made of ‘Cold Rolled Grain Oriented Silicon Steel’. Steel is very good ferromagnetic material. This kind of materials are very sensitive to be magnetized. That means whenever magnetic flux passes through, it will behave like magnet. Ferromagnetic substances have numbers of domains in their structure. Domain are very small region in the material structure, where all the dipoles are paralleled to same direction. In other words, the domains are like small small permanent magnet situated randomly in the structure of substance. These domains are arranged inside the material structure in such a random manner, that net resultant magnetic field of the said material is zero. Whenever external magnetic field or mmf is is applied to that substance, these randomly directed domains are arranged themselves in parallel to the axis of applied mmf. After removing this external mmf, maximum numbers of domains again come to random positions, but some few of them still remain in their changed position. Because of these unchanged domains the substance becomes slightly magnetized permanently. This magnetism is called "Spontaneous Magnetism". To neutralize this magnetism some opposite mmf is required to be applied. The magneto motive force or mmf applied in the transformer core is alternating. For every cycle, due to this domain reversal there will be extra work done. For this reason, there will be a consumption of electrical energy which is known as Hysteresis loss of transformer.
Consider a ring of ferromagnetic specimen of circumference L meter, cross-sectional area a m² and N turns of insulated wire as shown in the picture beside,

Let us consider, the current flowing through the coil is I amp,

Magnetizing force,

\[ H = \frac{NI}{L} \quad \text{or} \quad I = \frac{HL}{N} \]

Let, the flux density at this instant is B,

Therefore, total flux through the ring, \( \Phi = BXa \) Wb

As the current flowing through the solenoid is alternating, the flux produced in the iron ring is also alternating in nature, so the emf (e') induced will be expressed as,
According to Lenz's law this induced emf will oppose the flow of current, therefore, in order to maintain the current $I$ in the coil, the source must supply an equal and opposite emf. Hence the applied emf,

$$e = e' = -Na \frac{dB}{dt}$$

Energy consumed in short time $dt$, during which the flux density has changed,

$$= e \cdot I \cdot dt$$

$$= Na \frac{dB}{dt} \cdot I \cdot dt$$

$$= Na \frac{dB}{dt} \cdot \frac{-I}{N} \cdot X \cdot dt = aLHD\text{ joules}$$
Thus, total work done or energy consumed during one complete cycle of magnetism,

$$W = aL \int H.dB$$

Now $aL$ is the volume of the ring and $H.dB$ is the area of elementary strip of $B - H$ curve shown in the figure above,

$$\int H.dB$$

= total area enclosed by Hysteresis Loop.

Therefore, Energy consumed per cycle = volume of the ring $\times$ area of hysteresis loop.
In the case of transformer, this ring can be considered as magnetic core of transformer. Hence this work done is nothing but electrical energy loss in transformer core and this is known as hysteresis loss in transformer.

**What is Eddy Current loss?**

In transformer we supply alternating current in the primary, this alternating current produces alternating magnetizing flux in the core and as this flux links with secondary winding there will be induced voltage in secondary, resulting current to flow through the load connected with it. Some of the alternating fluxes of transformer may also link with other conducting parts like steel core or iron body of transformer etc. As alternating flux links with these parts of transformer, there would be an locally induced emf. Due to these emfs there would be currents which
will circulate locally at that parts of the transformer. These circulating current will
not contribute in output of the transformer and dissipated as heat. This type of
energy loss is called eddy current loss of transformer. This was a broad and
simple explanation of eddy current loss. The detail explanation of this loss is not in
the scope of discussion in that chapter.
Open Circuit Test and Short Circuit Test on Transformer

These two tests are performed on a transformer to determine (i) equivalent circuit of transformer (ii) voltage regulation of transformer (iii) efficiency of transformer. The power required for these **Open Circuit test and Short Circuit test on transformer** is equal to the power loss occurring in the transformer.

Open Circuit Test on Transformer

The connection diagram for **open circuit test on transformer** is shown in the figure. A voltmeter, wattmeter, and an ammeter are connected in the LV side of the transformer as shown. The voltage at rated frequency is applied to the LV side with the help of a variac of variable ratio auto transformer. The HV side of the transformer is kept open. Now with the help of variac applied voltage is slowly increased until the voltmeter gives reading equal to the rated voltage of the LV side. After reaching at rated LV side voltage, all three instruments reading (Volmeter, Ammeter and Wattmeter readings) are recorded. The ammeter reading gives the no load current $I_e$. As no load current $I_e$ is quite small compared to rated current of the transformer, the voltage drops due to this current then can be taken as negligible. Since, voltmeter reading $V_1$ can be considered equal to secondary induced voltage of the transformer. The input power during test is indicated by wattmeter reading. As the transformer is open circuited, there is no output hence the input power here consists of core losses in transformer and copper loss in transformer during no load condition. But as said earlier, the no load current in the transformer is quite small compared to full load current so copper loss due to the small no load current can be neglected. Hence the wattmeter reading can be taken as equal to core losses in transformer. Let us consider wattmeter reading is $P_o$.

$$P_o = \frac{V_1^2}{R_m}$$

Where $R_m$ is shunt branch resistance of transformer.

If, $Z_m$ is shunt branch impedance of transformer.

Then, $Z_m = \frac{V_1}{I_e}$.

Therefore, if shunt branch reactance of transformer is $X_m$.

Then, $\left(\frac{1}{X_m}\right)^2 = \left(\frac{1}{Z_m}\right)^2 - \left(\frac{1}{R_m}\right)^2$

These values are referred to the LV side of transformer as because the test is conducted on LV side of transformer. These values could easily be referred to HV side by multiplying these values with square of transformation ratio.

Therefore it is seen that the **open circuit test on transformer** is used to determine core losses in transformer and parameters of shunt branch of the equivalent circuit of transformer.
Short Circuit Test on Transformer

The connection diagram for short circuit test on transformer is shown in the figure. A voltmeter, wattmeter, and an ammeter are connected in HV side of the transformer as shown. The voltage at rated frequency is applied to that HV side with the help of a variac of variable ratio auto transformer.

The LV side of the transformer is short circuited. Now with help of variac applied voltage is slowly increase until the ammeter gives reading equal to the rated current of the HV side. After reaching at rated current of HV side, all three instruments reading (Voltmeter, Ammeter and Wattmeter readings) are recorded. The ammeter reading gives the primary equivalent of full load current $I_L$. As the voltage, applied for full load current in short circuit test on transformer, is quite small compared to rated primary voltage of the transformer, the core losses in transformer can be taken as negligible here.
Let's, voltmeter reading is $V_{sc}$. The input power during test is indicated by wattmeter reading. As the transformer is short circuited, there is no output hence the input power here consists of copper losses in transformer. Since, the applied voltage $V_{sc}$ is short circuit voltage in the transformer and hence it is quite small compared to rated voltage so core loss due to the small applied volate can be neglected. Hence the wattmeter reading can be taken as equal to copper losses in transformer. Let us consider wattmeter reading is $P_{sc}$.

$$P_{sc} = R_e I_L^2$$
Where $R_e$ is equivalent resistance of transformer.
If, $Z_e$ is equivalent impedance of transformer.
Then, $Z_e = \frac{V_{sc}}{I_L}$.
Therefore, if equivalent reactance of transformer is $X_e$
Then, $X_e^2 = Z_e^2 - R_e^2$

These values are referred to the HV side of transformer as because the test is conducted on HV side of transformer. These values could easily be referred to LV side by dividing these values with square of transformation ratio.

Therefore it is seen that the **Short Circuit test on transformer** is used to determine **copper loss in transformer** at full load and parameters of approximate **equivalent circuit of transformer**.
Auto Transformer

What is Auto Transformer?

**Auto transformer** is kind of electrical transformer where primary and secondary shares same common single winding.

Theory of Auto Transformer

In **Auto Transformer**, one single winding is used as primary winding as well as secondary winding. But in two windings transformer two different windings are used for primary and secondary purpose. A diagram of auto transformer is shown below.

The winding AB of total turns $N_1$ is considered as primary winding. This winding is tapped from point ‘C’ and the portion BC is considered as secondary. Let's assume the number of turns in between points ‘B’ and ‘C’ is $N_2$.

![Auto Transformer Diagram](image)

If $V_1$ voltage is applied across the winding in between ‘A’ and ‘C’. So voltage per turn in this winding is $V_1/N_1$. Hence, the voltage across the portion BC of the winding, will be $V_1/N_1 \times N_2$ and from the figure above, this voltage is $V_2$.

Hence, $V_1/N_1 \times N_2 = V_2$

$V_2/V_1 = N_2/N_1 = \text{Constant} = k$

As BC portion of the winding is considered as secondary, it can easily be understood that value of constant ‘k’ is nothing but turns ratio or voltage ratio of that Auto Transformer.
When load is connected between secondary terminals i.e. between ‘B’ and ‘C’, load current \( I_2 \) starts flowing. The current in the secondary winding or common winding is the difference of \( I_2 \) & \( I_1 \).

**Copper savings in Auto Transformer**

Now we will discuss the savings of copper in auto transformer compared to conventional two windings electrical power transformer.

We know that:

Weight of copper of any winding depends upon its length and cross-sectional area.

Again length of conductor in winding is proportional to its number of turns and cross-sectional area varies with rated current.

So weight of copper in winding is directly proportional to product of number of turns and rated current of the winding.

Therefore, weight of copper in the section AC proportional to

\[(N_1 - N_2)I_1\]

and similarly, weight of copper in the section BC proportional to

\[N_2(I_2 - I_1)\]

Hence, total weight of copper in the winding of Auto Transformer proportional to

\[(N_1 - N_2)I_1 + N_2(I_2 - I_1)\]

\[\Rightarrow N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1\]

\[\Rightarrow N_1I_1 + N_2I_2 - 2N_2I_1\]

\[\Rightarrow 2N_1I_1 - 2N_2I_1\]

\[\Rightarrow 2(N_1I_1 - N_2I_1)\]

In similar way it can be proved, the weight of copper in two winding transformer is proportional to,

\[N_1I_1 + N_2I_2\]

\[\Rightarrow 2N_1I_1\]

(Since, \( N_1I_1 = N_2I_2 \))

Let's assume, \( W_a \) and \( W_{tw} \) are weight of copper in auto transformer and two winding transformer respectively,
Hence, \[ W_a/W_{tw} = 2(N_1I_1 - N_2I_1)/(N_1I_1) \]
\[ = (N_1I_1 - N_2I_1)/(N_1I_1) \]
\[ = 1 - (N_2I_1)/(N_1I_1) \]
\[ = 1 - N_2/N_1 \]
\[ = 1 - k \]

\[ \therefore W_a = W_{tw}(1 - k) \]
\[ \Rightarrow W_a = W_{tw} - kW_{tw} \]

\[ \therefore \text{Saving of copper in auto transformer compared to two winding transformer,} \]
\[ \Rightarrow W_{tw} - W_a = kW_{tw} \]

Auto transformer employs only single winding per phase as against two distinctly separate windings in a conventional power transformer.

**Advantages of using auto transformer.**

For transformation ratio = 2, the size of the auto transformer would be approximately 50% of the corresponding size of two winding transformer.

For transformation ratio say 20 however the size would be 95%. The saving in cost is of course not in the same proportion. The saving of cost is appreciable when the ratio of transformer is low, that is lower than 2.

**Disadvantages of using Auto Transformer**

But auto transformer has the following disadvantages:

1. Because of electrical conductivity of the primary and secondary windings the lower voltage circuit is liable to be impressed upon by higher voltage. To avoid breakdown in the lower voltage circuit, it becomes necessary to design the low voltage circuit to withstand higher voltage.
2. The leakage flux between the primary and secondary windings is small and hence the impedance is low. This results into severer short circuit currents under fault conditions.

3. The connections on primary and secondary sides have necessarily to be same, except when using interconnected starring connections. This introduces complications due to changing primary and secondary phase angle particularly in the case-by-case of delta / delta connection.

4. Because of common neutral in a star / star connected auto transformer it is not possible to earth neutral of one side only. Both their sides have to have their neutrality either earth or isolated.

5. It is more difficult to preserve the electromagnetic balance of the winding when voltage adjustment tappings are provided. It should be known that the provision of adjusting tapping on an auto transformer increases considerably the frame size of the transformer. If the range of tapping is very large, the advantages gained in initial cost is lost to a great event
Tertiary Winding of Transformer

What is tertiary winding? What is Three Winding Transformer?

In some high rating transformer, one winding, in addition to its primary and secondary winding, is used. This additional winding, apart from primary and secondary windings, is known as Tertiary Winding of Transformer. Because of this third winding, the transformer is called Three Winding Transformer or 3 Winding Transformer.

Advantages of using tertiary winding in transformer

Tertiary Winding is provided in Electrical Power Transformer to meet one or more of the following requirements
1. It reduces the unbalancing in the primary due to unbalancing in three phase load
2. It redistributes the flow of fault current
3. Sometime it is required to supply an auxiliary load in different voltage level in addition to its main secondary load. This secondary load can be taken from tertiary winding of three winding transformer.
4. As the tertiary winding is connected in delta formation in 3 winding transformer, it assists in limitation of fault current in the event of a short circuit from line to neutral.

Stabilization by tertiary winding of transformer

In star - star transformer comprising three single units or a single unit with 5 limb core offers high impedance to the flow of unbalanced load between the line and neutral. This is because, in both of these transformer, there is very low reluctance return path of unbalanced flux.
If any transformer has N - turns in winding and reluctance of the magnetic path is $R_L$, then,

\[ \text{mmf} = N.I = \Phi R_L \quad \text{..... (1)} \]
Where $I$ and $\Phi$ are current and flux in the transformer.
Again, induced voltage $V = 4.44\Phi fN$
\[ \Rightarrow V \propto \Phi \]
\[ \Rightarrow \Phi = K.V \text{ (Where K is constant)...... (2)} \]

Now, from equation (1) & (2), it can be rewritten as,

\[ N.I = K.V.R_L \]
\[ \Rightarrow \frac{V}{I} = \frac{N}{(K.R_L)} \]
\[ \Rightarrow Z = \frac{N}{(K.R_L)} \]
\[ \Rightarrow Z \propto \frac{1}{R_L} \]

From this above mathematical expression it is found that impedance is inversely proportional to reluctance. The impedance offered by the return path of unbalanced load
current, is very high where very low reluctance return path is provided for unbalanced flux.

In other words, very high impedance to the flow of unbalanced current in 3 phase system between line and neutral.

Any unbalanced current in three phase system can be divided into three sets of components like wise positive sequence, negative sequence and zero sequence components.

The zero sequence current actually co-phasial current in three lines. If value of co-phasial current in each line is \(I_0\), then total current flows through the neutral of secondary side of transformer is \(I_n = 3I_0\).

This current can not be balanced by primary current as the zero sequence current cannot flow through the isolated neutral-star connected primary. Hence the said current in the secondary side set up a magnetic flux in the core.

As we earlier in this chapter low reluctance path is available for the zero sequence flux in a bank of single phase units and in the 5 limb core consequently the impedance offered to the zero sequence current is very high.

The delta connected tertiary winding of transformer permits the circulation of zero sequence current in it. This circulating current in this delta winding balance the zero sequence component of unbalance load, hence prevent unnecessary development of unbalance zero sequence flux in the transformer core.

In few words it can be said that, placement of tertiary winding in star - star - neutral transformer considerably reduces the zero sequence impedance of transformer.
Rating of tertiary winding of transformer

Rating of tertiary winding of transformer depends upon its use. If it has to supply additional load, its winding cross-section and design philosophy is decided as per load and three phase dead short circuit on its terminal with power flow from both sides of HV & MV.

In case it is to be provided for stabilizing purpose only, its cross-section and design has to be decided from thermal and mechanical consideration for the short duration fault currents during various fault conditions single line-to-ground fault being the most onerous.

Parallel operation of Transformers

Why "parallel operation of transformers" is required?

It is economical to installed numbers of smaller rated transformers in parallel than installing a bigger rated electrical power transformer. This has mainly the following advantages,

1) To maximize electrical power system efficiency: Generally electrical power transformer gives the maximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on only those transformers which will give the total demand by running nearer to its full load rating for that time. When load increases we can switch no one by one other transformer connected in parallel to fulfill the total demand. In this way we can run the system with maximum efficiency.

2) To maximize electrical power system availability: If numbers of transformers run in parallel we can take shutdown any one of them for maintenance purpose. Other parallel transformers in system will serve the load without total interruption of power.

3) To maximize power system reliability: if nay one of the transformers run in parallel, is tripped due to fault other parallel transformers is the system will share the load hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.

4) To maximize electrical power system flexibility: Always there is a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future, there must be a provision of connecting transformers in system in parallel to fulfill the extra demand because it is not economical from business point of view to install a bigger rated single transformer by forecasting the increased future demand as it is unnecessary investment of money. Again if future demand is decreased, transformers running in parallel can be removed from system to balance the capital investment and its return.
Conditions for parallel operation of transformers.

When two or more transformers are run in parallel they must satisfy the following conditions for satisfactory performance. These are the conditions for parallel operation of transformers.

a) same voltage ratio of transformer
b) same percentage impedance
c) same polarity
d) same phase sequence

Same voltage ratio

If two transformers of different voltage ratio, are connected in parallel with same primary supply voltage, there will be a difference in secondary voltages. Now say the secondary of these transformers are connected to same bus, there will be a circulating current between secondaries and therefore between primaries also. As the internal impedance of transformer is small, a small voltage difference may cause sufficiently high circulating current causing unnecessary extra I^2R loss.

Same percentage impedance

The current shared by two transformers running in parallel should be proportional to their MVA ratings. Again, current carried by these transformers are inversely proportional to their internal impedance. From these two statements it can be said that impedance of transformers running in parallel are inversely proportional to their MVA ratings. In other words percentage impedance or per unit values of impedance should be identical for all the transformers run in parallel.

Same polarity

Polarity of all transformers run in parallel should be same otherwise huge circulating current flows in the transformer but no load will be fed from these transformers. Polarity of transformer means the instantaneous direction of induced emf in secondary. If the instantaneous directions of induced secondary emf in two transformers are opposite to each other when same input power is fed to the both of the transformers, the transformers are said to be in opposite polarity. If the instantaneous directions of induced secondary emf in two transformers are same when same input power is fed to the both of the transformers, the transformers are said to be in same polarity.

Same phase sequence

The phase sequence or the order in which the phases reach their maximum positive voltage, must be identical for two parallel transformers. Otherwise, during the cycle, each pair of phases will be short circuited.
The above said conditions must be strictly followed for parallel operation of transformers but totally identical percentage impedance of two different transformers is difficult to achieve practically that is why the transforms run in parallel may not have exactly same percentage impedance but the values would be as nearer as possible.

**Transformer Cooling System**

The main source of heat generation in transformer is its copper loss or $I^2R$ loss. Although there are other factors contribute heat in transformer such as hysteresis & eddy current losses but contribution of $I^2R$ loss dominate them. If this heat is not dissipated properly, the temperature of the transformer will rise continually which may cause damages in paper insulation and liquid insulation medium of transformer. So it is essential to control the temperature within permissible limit to ensure the long life of transformer by reducing thermal degradation of its insulation system. In Electrical Power transformer we use external transformer cooling system to accelerate the dissipation rate of heat of transformer. There are different transformer cooling methods available for transformer, we will now explain one by one.

**Different Transformer Cooling Methods**

For accelerating cooling different transformer cooling methods are used depending upon their size and ratings. We will discuss these one by one below,

**ONAN Cooling of Transformer**

This is the simplest transformer cooling system. The full form of ONAN is "Oil Natural Air Natural". Here natural convectional flow of hot oil is utilized for cooling. In convectional circulation of oil, the hot oil flows to the upper portion of the transformer tank and the vacant place is occupied by cold oil. This hot oil which comes to upper side, will dissipate heat in the atmosphere by natural conduction, convection & radiation in air and will become cold. In this way the oil in the transformer tank continually circulate when the transformer put into load. As the rate of dissipation of heat in air depends upon dissipating surface of the oil tank, it is essential to increase the effective surface area of the tank. So additional dissipating surface in the form of tubes or radiators connected to the transformer tank. This is known as radiator of transformer or radiator bank of transformer. We have shown below a simplest form on Natural Cooling or ONAN Cooling arrangement of an earthing transformer below.
**ONAF Cooling of Transformer**

Heat dissipation can obviously be increased, if dissipating surface is increased but it can be make further faster by applying forced air flow on that dissipating surface. Fans blowing air on cooling surface is employed. Forced air takes away the heat from the surface of radiator and provides better cooling than natural air. The full form of ONAF is "Oil Natural Air Forced". As the heat dissipation rate is faster and more in ONAF transformer cooling method than ONAN cooling system, electrical power transformer can be put into more load without crossing the permissible temperature limits.

**OFAF Cooling of Transformer**

In Oil Forced Air Natural cooling system of transformer, the heat dissipation is accelerated by using forced air on the dissipating surface but circulation of the hot oil in transformer tank is natural convectional flow.

The heat dissipation rate can be still increased further if this oil circulation is accelerated by applying some force. In OFAF cooling system the oil is forced to circulate within the closed loop of transformer tank by means of oil pumps. OFAF means "Oil Forced Air Forced" cooling methods of transformer. The main advantage of this system is that it is compact system and for same cooling capacity OFAF occupies much less space than farmer two systems of transformer cooling. Actually in Oil Natural cooling system, the heat comes out from conducting part of the transformer is displaced from its position, in slower rate due to convectional flow of oil but in forced oil cooling system the heat is displaced from its origin as soon as it comes out in the oil, hence rate of cooling becomes faster.
**OFWF Cooling of Transformer**

We know that ambient temperature of water is much less than the atmospheric air in same weather condition. So water may be used as better heat exchanger media than air. In OFWF cooling system of transformer, the hot oil is sent to a oil to water heat exchanger by means of oil pump and there the oil is cooled by applying sowers of cold water on the heat exchanger's oil pipes. OFWF means "Oil Forced Water Forced" cooling in transformer.

**ODAF Cooling of Transformer**

ODAF or Oil Directed Air Forced Cooling of Transformer can be considered as the improved version of OFAF. Here forced circulation of oil directed to flow through predetermined paths in transformer winding. The cool oil entering the transformer tank from cooler or radiator is passed through the winding where gaps for oil flow or pre-decided oil flowing paths between insulated conductor are provided for ensuring faster rate of heat transfer. ODAF or Oil Directed Air Forced Cooling of Transformer is generally used in very high rating transformer.

**ODWF Cooling of Transformer**

ODAF or Oil Directed Water Forced Cooling of Transformer is just like ODAF only difference is that here the hot oil is cooled in cooler by means of forced water instead of air. Both of these transformer cooling methods are called Forced Directed Oil Cooling of transformer
Core of Transformer

Purpose of Transformer Core

In a electrical power transformer there are primary, secondary and may be tertiary windings. The performance of a transformer mainly depends upon the flux linkages between these windings. For efficient flux linking between these winding one low reluctance magnetic path common to all windings, should be provided in the transformer. This low reluctance magnetic path in transformer is known as core of transformer.

Influence of Diameter of Transformer Core

Let us consider, the diameter of transformer core be ‘D’

Then, cross-sectional area of the core,

\[ A = \pi D^2/4, \]

Now, voltage per turn

\[ E = 4.44 \cdot \phi_m \cdot f \]
\[ = 4.44 \cdot A \cdot B_m \cdot f \]

Where \( B_m \) is the maximum flux density of the core.

\[ = 4.44 \pi D^2 B_m f / 4 \]

\( E \) is proportional to \( D^2 \)

Therefore voltage per turn is increased with increase in diameter of transformer core.

Again if voltage across the winding of transformer is \( V \)

Then \( V/N = e = 4.44 \pi D^2 B_m f / 4 \),

Where \( N \) is the number of turns in winding.

If \( V \) is constant, \( e \) is inversely proportional to \( N \).

And hence \( D^2 \) is inversely proportional to \( N \).

So diameter of the core is increased, the number of turns in the transformer winding reduced.

Reduction of number of turns, reduction in height of the core legs. In-spite of reduction of core legs height, increased in core diameter, results, increased in overall diameter of
magnetic **core of transformer**. This increased steel weight ultimately leads to **increased core losses in transformer**.

Increased diameter of the core leads to increase the mean diameter on the winding. In spite of increased diameter of the winding turns, reduced the number of turns in the winding, leads to **less copper loss in transformer**.

So we go on increasing diameter of the transformer core, losses in the transformer core will be increased but at the same time load loss or **copper loss in transformer** is reduced.

On the other hand if diameter of the core is decreased, the weight of the steel in the core is reduced which leads to less **core loss of transformer**, but in the same time this leads to increase in number of turns in the winding, means increase in copper weight, which leads to extra **copper loss in transformer**.

So diameter of the core must be optimized during **design of transformer core**, considering the both aspect.

**Material for Transformer Core**

The main problem with **transformer core** is, its hysteresis loss and **eddy current loss in transformer**. **Hysteresis loss in transformer** mainly depends upon its core materials. It is found that a small quantity of silicon alloyed with low carbon content steel produces, material for transformer core which has low hysteresis loss and high permeability. As the increasing demand of power ratings, it is required to further reduce the core losses and for that other technique is employed on steel, which is known as cold rolling.

This technique arrange the orientation of grain in ferromagnetic steel in the direction of rolling. The core steel which has under gone through the both silicon alloying and cold rolling treatments, is commonly known as CRGOS or Cold Rolled Grain Oriented Silicon Steel. This material is now universally used for manufacturing for transformer core. Although this material has low specific iron loss but still it has some disadvantages, Like it is susceptible to increase loss due to flux flow in direction other than grain orientation and it also susceptible to impaired performance due to impact of bending, blanking the cutting CRGOS sheet. Both surfaces of the sheets are provided with an insulating of oxide coating.

**Optimum Design of Cross – Section of Transformer Core**

The maximum flux density of CRGO steel is about **1.9 Tesla**. Means the steel becomes saturated at the flux density 1.9 Tesla. One important criterion for **design of transformer core**, is that, it must not be saturated during transformer’s normal operation mode. Voltages of transformer depend upon its total magnetizing flux. Total magnetizing flux through core is nothing but product of flux density and cross – sectional area of the core. Hence, flux density of a core can be controlled by adjusting the cross sectional area of the core during its design.
The idea shape of cross-section of a transformer core is circular. For making perfect circular cross section, each and every successive lamination steel sheet should be cut in different dimension and size. This is absolutely uneconomical for practical manufacturing. In reality, manufacturers use different groups or packets of predefined number of same dimension lamination sheets. The group or packet is a block of laminated sheets with a predefined optimum height (thickness). The core is assembly of these blocks in such a successive manner as per their size from core central line that it gives a optimum circular shape of the cross-section. Such typical cross-section is shown in the figure below.

Oil ducts are needed for cooling the core. Cooling ducts are necessary because hot-spot temperature may rise dangerously high and their number depends on the core diameter, materials used for core. In addition to that clamp plates made of steel are needed on either sides of the core to clamping the laminations. The sheet steel lamination blocks, oil ducts, and clamping plates all should lie within the peripheral of optimum core circle.

The net sectional area is calculated from the dimensions of various packets and allowance is made for the space lost between lamination (known as stacking factor) which for sheet steel of 0.28 mm thickness with insulation coating is approximately 0.96. Area is also deducted for oil ducts. The ratio of net cross-sectional area of core to the gross cross-sectional area inside the imaginary peripheral circle is known as Utilization Factor of transformer core. By increasing numbers of steps of improves the Utilization Factor but at the same time it increases manufacturing cost. Optimum numbers of steps are between 6 (for smaller diameter) to 15 (larger diameter).

Manufacturing of transformer core

During core manufacturing in factory some factors are taken into consideration,

a) Higher reliability
b) Reduction in iron loss in transformer and magnetizing current
c) Lowering material cost and labor cost
d) abatement of noise levels
Quality checking is necessary at every step of manufacturing to ensure quality and reliability. The sheet steel must be tested for ensuring the specific core loss or iron loss values. The lamination should be properly checked and inspected visually, rusty and bend lamination to be rejected. For reducing the transformer noises the laminations should be tightly clamped together and punch holes should be avoided as far as possible to minimize cross flux iron losses. The air gap at the joint of limbs and yokes should be reduced as much as possible for allowing maximum smooth conducting paths for magnetizing current.

**Corner Jointing of Limbs with Yokes**

Core losses in transformer mainly due to,
1) magnetic flux flow along the direction of the grain orientation,
2) magnetic flux flow perpendicular to the direction of the grain orientation, this is also known as cross grain iron losses. The cross grain loss mainly occurs in the zones of Corner Jointing of Limbs with Yokes and it can be controlled to some extent by applying special corner jointing techniques. There are normally two types of joints used in transformer core

1) Interleaved Joints
2) Mited Joints

![Three Limbs Core Interleaved Joints](image)

**Interleaved Joints in transformer core**

Interleaved Joint in transformer core is the simplest form of joints. This joint is shown in the figure. The flux leaves and enters at the joint in perpendicular to grain orientation. Hence Cross Grain losses is high in this type of joints. But considering the low manufacturing cost it is preferable to use in small rating transformer.
Mitred Joints in transformer core

Here the laminations are cut at 45°. The limbs and yoke lamination edges are placed face to face at the Mitred Joints in transformer core. Here the flux enters and leaves the laminations gets smooth path in the direction of its flow. Hence cross grain loss is minimum here. However it involves extra manufacturing cost but it is preferable to use in electrical power transformer where loss minimization is of the main criteria of design of transformer core.
Insulating Transformer Oil

Introduction of Insulating Oil

Insulating oil in an electrical power transformer is commonly known as Transformer Oil. It is normally obtained by fractional distillation and subsequent treatment of crude petroleum. That is why this oil is also known as Mineral Insulating Oil. Transformer Oil serves mainly two purposes one it is liquid insulation in electrical power transformer and two it dissipates heat of the transformer i.e. acts as coolant. In addition to these, this oil serves other two purposes, it helps to preserve the core and winding as these are fully immersed inside oil and another important purpose of this oil is, it prevents direct contact of atmospheric oxygen with cellulose made paper insulation of windings, which is susceptible to oxidation.

Types of Transformer Oil

Generally there are two types of Transformer Oil used in transformer,

1. Paraffin based Transformer Oil

2. Naphtha based Transformer Oil

Naphtha oil is more easily oxidized than Paraffin oil. But oxidation product i.e. sludge in the naphtha oil is more soluble than Paraffin oil. Thus sludge of naphtha based oil is not precipitated in bottom of the transformer. Hence it does not obstruct convection circulation of the oil, means it does not disturb the transformer cooling system. But in the case of Paraffin oil although oxidation rate is lower than that of Naphtha oil but the oxidation product or sludge is insoluble and precipitated at bottom of the tank and obstruct the transformer cooling system. Although Paraffin based oil has above mentioned disadvantage but still in our country it is generally used because of its easy availability. Another problem with paraffin based oil is its high pour point due to the wax content, but this does not effect its use due to warm climate condition of India.

Properties of Transformer Insulating Oil

Some specific parameters of insulating oil should be considered to determined the serviceability of that oil.

Parameters of Transformer Oil

The parameters of Transformer Oil are categorised as,

2. **Chemical Parameter** - Water Content, Acidity, Sludge Content.

3. **Physical Parameters** - Inter Facial Tension, Viscosity, Flash Point, Pour Point.

**Electrical Parameter of Transformer Oil**

**Dielectric Strength of Transformer Oil**

*Dielectric Strength of Transformer Oil* is also known as *Breakdown Voltage of transformer oil* or *BDV of transformer oil*. Break down voltage is measured by observing at what voltage, sparking strants between two electrodes immersed in the oil, separated by specific gap. low value of BDV indicates presence of moisture content and conducting substances in the oil. For measuring *BDV of transformer oil*, portable BDV measuring kit is generally available at site. In this kit, oil is kept in a pot in which one pair of electrodes are fixed with a gap of **2.5 mm** (in some kit it 4mm) between them. Now slowly rising voltage is applied between the electrodes. Rate of rise of voltage is generally controlled at 2KV/s and observe the voltage at which sparking starts between the electrodes. That means at which voltage Dielectric Strength of transformer oil between the electrodes has been broken down.
Generally this measurement is taken 3 to 6 times in same sample of oil and the average value of these reading is taken. BDV is important and popular test of transformer oil, as it is primary indication of health of oil and it can be easily carried out at site.

Dry and clean oil gives BDV results, better than the oil with moisture content and other conducting impurities. Minimum **Breakdown Voltage of transformer oil** or **Dielectric Strength of transformer oil** at which this oil can safely be used in transformer, is considered as 30 KV.

**Specific Resistance ( Resistivity ) of Transformer Oil**

This is another important property of transformer oil. This is measure of DC resistance between two opposite sides of one cm$^3$ block of oil. Its unit is taken as ohm-cm at specific temperature. With increase in temperature the resistivity of oil decreases rapidly. Just after charging a transformer after long shut down, the temperature of the oil will be at ambient temperature and during full load the temperature will be very high and may go up to 90°C at over load condition. So resistivity of the insulating oil must be high at room temperature and also it should have good value at high temperature as well. That is why specific resistance or resistivity of transformer oil should be measured at 27°C as well as 90°C.

Minimum standard Specific Resistance of Transformer oil at 90°C is $35 \times 10^{12}$ ohm – cm and at 27°C it is $1500\times10^{12}$ ohm – cm.

**Dielectric Dissipation Factor of tan delta of Transformer oil**

Dielectric Dissipation Factor is also known as loss factor or **tan delta of transformer oil**. When an insulating materials is placed between live part and grounded part of an electrical equipment, leakage current will flow.

As insulating material is dielectric in nature the current through the insulation ideally leads the voltage by 90°.

Here voltage means the instantaneous voltage between live part and ground of the equipment. But in reality no insulating materials are perfect dielectric in nature.

Hence current through the insulator will lead the voltage with an angle little bit shorter than 90°.

**Tangent of the angle by which it is short of 90° is called Dielectric Dissipation Factor or simply tan delta of transformer oil.**

More clearly, the leakage current through an insulation does have two component one is capacitive or reactive and other one is resistive or active. Again it is clear from above
diagram, value of ‘δ’ which is also known as loss angle,

\begin{center}
\textbf{Loss Angle}
\end{center}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{loss_angle_diagram}
\end{figure}

is smaller, means resistive component of the current $I_R$ is smaller which indicates high resistive property of the insulating material. High resistive insulation is good insulator.

Hence it is desirable to have loss angle as small as possible. So we should try to keep the value of tanδ as small as possible. High value of this tanδ is an indication of presence of contaminants in transformer oil. Hence there is a clear relationship between tanδ and resistivity of insulating oil.

If resistivity of the insulating oil is decreased, the value of tandelta increases and vice versa. So both resistivity test and tan delta test of transformer oil are not normally required for same piece of insulator or insulating oil.

In one sentence it can be said that, tanδ is measure of imperfection of dielectric nature of insulation materials like oil.

**Chemical Parameters of Transformer Oil**

**Water Content in Transformer Oil**

Moisture or Water Content in Transformer Oil is highly undesirable as it affects adversely the dielectric properties of oil. The water content in oil also affects the paper insulation of the core and winding of transformer. Paper is highly hygroscopic in nature. Paper absorbs maximum amount of water from oil which affects paper insulation property as well as reduced its life.

But in loaded transformer, oil becomes hotter, hence the solubility of water in oil increases as a result the paper releases water and increase the water content in transformer oil. Thus the temperature of the oil at the time of taking sample for test is very important.
During oxidation acid are formed in the oil the acids give rise the solubility of water in the oil. Acid coupled with water further decompose the oil forming more acid and water. This rate of degradation of oil increases. The water content in oil is measured as ppm(parts per million unit). Water content in oil is allowed up to 50 ppm as recommended by IS – 335(1993). The accurate measurement of water content at such low levels requires very sophisticated instrument like Coulometric Karl Fisher Titrator.

**Acidity of Transformer Oil**

**Acidity of transformer oil**, is harmful property. If oil becomes acidic, water content in the oil becomes more soluble to the the oil. Acidity of oil detories the insulation property of paper insulation of winding.

**Acidity accelerates the oxidation process in the oil.**

Acid also includes rusting of iron in presence of moisture. The acidity of transformer oil is measure of its acidic constituents of contaminants. Acidity of oil is express in mg of KOH required to neutralize the acid present in a gram of oil. This is also known as neutralization number.

**Physical Parameters of transformer oil**

**Inter Facial Tension of Transformer Oil**

Inter Facial Tension between the water and oil interface is the way to measure molecular attractive force between water and oil. It is measured in Dynes/cm or miliNeuton/meter. Inter facial Tension is exactly useful for determining the presence of polar contaminants and oil decay products. Good new oil generally exhibits high inter facial tension. Oil oxidation contaminants lower the IFT.

**Flash Point of Transformer Oil**

**Flash point of transformer oil** is the temperature at which oil gives enough vapors to produce a flammable mixture with air. This mixture gives momentary flash on application of flame under standard condition. Flash point is important because it specifies the chances of fire hazard in the transformer. So it is desirable to have very high flash point of transformer oil. In general it is more than 140o(>10o).

**Pour Point of Transformer Oil**

It is the minimum temperature at which oil just start to flow under standard test condition. Pour Point of Transformer Oil is an important property mainly at the places where climate is extremely cold. If the oil temperature falls below the pour point, transformer oil stops convection flowing and obstruct cooling in transformer. Paraffin based oil has higher value of pour point, compared to Naphtha based oil, but in India like country, it does not effect
the use of Paraffin oil due to its warm climate condition. Pour Point of transformer oil mainly depends upon wax content in the oil. As Paraffin based oil has more wax content, it has higher pour point.

**Viscosity of Transformer Oil**

In few words, *Viscosity of Transformer Oil* can be said that *Viscosity is the resistance of flow, at normal condition*. Obviously resistance to flow of transformer oil means obstruction of convection circulation of oil inside the transformer. A good oil should have low viscosity so that it offers less resistance to the convectional flow of oil thereby not affecting the cooling of transformer. Low *viscosity of transformer oil* is essential, but it is equally important that, the viscosity of oil should increase as less as possible with decrease in temperature. Every liquid becomes more viscous if temperature decreases.

**DGA or Dissolved Gas Analysis of Transformer Oil**

Whenever *electrical power transformer* goes under abnormal thermal and electrical stresses, certain gases are produced due to decomposition of *transformer insulating oil*, when the fault is major, the production of decomposed gases are more and they get collected in Buchholz relay. But when abnormal thermal and electrical stresses are not significantly high the gases due to decomposition of *transformer insulating oil* will get enough time to dissolve in the oil. Hence by only monitoring the Buchholz relay it is not possible to predict the condition of the total internal healthiness of *electrical power transformer*. That is why it becomes necessary to analyse the quantity of different gasses dissolved in transformer oil in service. From *Dissolved Gas Analysis of Transformer Oil* or *DGA of Transformer Oil*, one can predict the actual condition of internal health of a transformer. It is preferable to conduct the *DGA test of transformer oil* in routine manner to get prior information about the trend of deterioration of transformer health and life.

Actually in *Dissolved Gas Analysis of Transformer Oil* or *DGA of Transformer Oil* test, the gases in oil are extracted from oil and analyse the quantity of gasses in a specific amount of oil. By observing percentages of different gasses present in the oil, one can predict the internal condition of transformer.

Generally the gasses found in the oil in service are hydrogen (H₂), methane(CH₄), Ethane (C₂H₆), ethylene(C₂H₄), acetylene (C₂H₃), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen(N₂) and oxygen(O₂).

Most commonly used method of determining the content of these gases in oil, is using a Vacuum Gas Extraction Apparatus and Gas Chronographs. By this apparatus first gasses are extracted from oil by stirring it under vacuum. These extracted gasses are then introduced in gas Chronographs for measurement of each component.
Generally it is found that hydrogen and methane are produced in large quantity if internal temperature of power transformer rises up to 150°C to 300°C due to abnormal thermal stresses. If temperature goes above 300°C, ethylene(C$_2$H$_4$) are produced in large quantity. At the temperature is higher than 700°C large amount of hydrogen(H$_2$) and ethylene(C$_2$H$_4$) are produced. Ethylene(C$_2$H$_4$) is indication of very high temperature hot spot inside electrical transformer. If during DGA test of transformer oil, CO and CO$_2$ are found in large quantity it is predicted that there is decomposition of proper insulation.

**Furfural Test or Furfuraldehyde Analysis of Transformer Oil**

Transformer core and winding have mainly paper insulation. Base of paper is cellulose. The Cellulose has a structure of long chain of molecules. As the paper becomes aged, these long chains are broken into number of shorter parts. This phenomenon we often observe in our home. The pages of very old books become very much brittle. In transformer, the aging affect of paper insulation is accelerated due to oxidation occurs in oil. When insulating paper becomes mechanically weak, it can not withstand the mechanical stresses applied during electrical short circuit and leads to electrical breakdown.

It is therefore necessary to monitor the condition of paper insulation inside a power transformer.

It is not possible to bring out a piece of paper insulation from a transformer in service for testing purpose. But we are lucky enough, that there is a testing technique developed, where we can examine the condition of paper insulation without touching it. The method is called** Furfuradehyde Analysis** of in short **Furfural test**.

Although by Dissolved Gas Analysis one can predict the condition of the paper insulation primarily, but it is not very sensitive method. There is a guide line in IEC - 599, where it is told that if the ratio of CO$_2$ and CO in DGA results is more than 11, it is predicted that the condition of paper insulation inside the transformer is not good. A healthy cellulose insulation gives that ratio in a range of 4 to 11. But still it is not a very sensitive way of monitoring the condition of paper insulation. Because CO$_2$ and CO gases also produced during oil breakdown and sometimes the ratio may misleads the prediction.

When oil is soaked into paper, it is damaged by heat and some unique oil soluble compounds are realized and dissolved in the oil along with CO$_2$ and CO. These compounds belong to the Furfuraldehyde group. These are some times called Furfural in short. Among all Furfurals compounds 2 - Furfural is the most predominant. These Furfural family compound can only be released from destructive heating of cellulose or paper. **Furfuraldehyde Analysis** is very sensitive as because damage of few grams of paper is noticeable in the oil even of a very large size transformer. It is a very significant
diagnostic test. It is best test for assessing life of transformer. The rate of rise of percentage of Furfurals products in oil, with respect to time, is used for assessing the condition and remaining life of paper insulation in power transformer.

**Over Fluxing in Transformer**

**Causes of Over Fluxing in Transformer**

As per present day transformer design practice, the peak rated value of the flux density is kept about **1.7 to 1.8 Tesla**, while the saturation flux density of CRGD steel sheet of *core of transformer* is of the order of **1.9 to 2 Tesla** which corresponds to about 1.1 times the rated value. If during operation, an *electrical power transformer* is subjected to carry rather swallow more than above mentioned flux density as per its design limitations, the transformer is said to have faced over fluxing problem and consequent bad effects towards its operation and life.

Depending upon the design and saturation flux densities and the thermal time constants of the heated component parts, a transformer has some over excitation capacity. I.S. specification for *electrical power transformer* does not stipulate the short time permissible over excitation, though in a round about way it does indicate that the maximum over fluxing in transformer shall not exceed 110%.

The flux density in a transformer can be expressed by

\[
B = C \frac{V}{f},
\]

where, \(C = \text{constant,}\)
\(V = \text{Induced voltage,}\)
\(f = \text{Frequency.}\)

The magnetic flux density is, therefore, proportional to the quotient of voltage and frequency \((V/f)\).

*Over fluxing* can, therefore, occur either due to increase in voltage or decrease in frequency of both.

The probability of over fluxing is relatively high in step-up transformers in Power stations compared to step-down transformers in Sub- Stations, where voltage and frequency usually remain constant. However, under very abnormal system condition, over-fluxing trouble can arise in step-down Sub-Station transformers as well.
**Effect of Over Fluxing in Transformers**

The flux in a transformer, under normal conditions is confined to the core of transformer because of its high permeability compared to the surrounding volume.

When the flux density in the increases beyond saturation point, a substantial amount of flux is diverted to steel structural parts and into the air.

At saturation flux density the core steel will over heat.

Structural steel parts which are un-laminated and are not designed to carry magnetic flux will heat rapidly. Flux flowing in unplanned air paths may link conduction loops in the windings, loads, tank base at the bottom of the core and structural parts and the resulting circulating currents in these loops can cause dangerous temperature increase.

Under conditions of excessive over fluxing the heating of the inner portion of the windings may be sufficiently extreme as the exciting current is rich in harmonics. It is obvious that the levels of loss which occur in the winding at high excitation cannot be tolerated for long if the damage is to be avoided.

Physical evidences of damage due to over fluxing will vary with the degree of over excitation, the time applied and the particular design of transformer. The Table given below summarizes such physical damage and probable consequences.

<table>
<thead>
<tr>
<th>SL</th>
<th>Component involved</th>
<th>Physical evidences</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Metallic support and surfaces structure for core and coils</td>
<td>Discolouration or metallic parts and adjacent insulation, Possible carbonized material in oil. Evolution of combustible gas.</td>
<td>Contamination of oil and surfaces of insulation. Mechanical weakening of insulation. Loosing of structure. Mechanical structure</td>
</tr>
<tr>
<td>2</td>
<td>Windings</td>
<td>Discoloration winding insulation evolution of gas.</td>
<td>Electrical and mechanical weakening of winding insulation</td>
</tr>
<tr>
<td>3</td>
<td>Lead conductors.</td>
<td>Discoloration of conductor insulation or support, evolution of</td>
<td>Electrical and mechanical weakening of insulation, Mechanical Weakening of</td>
</tr>
</tbody>
</table>
4 Core laminations. Discoloration of insulating material in contact with core. Discoloration and carbonization of organic/lamination insulation **Evaluation of gas.** Electrical weakening of major insulation (winding to core) increased inter laminar eddy loss.

5 Tank Blistering of paints Contamination of oil if paint inside tank is blistered.

It may be seen that metallic support structures for core and coil, windings, lead conductors, core laminations, tank etc. may attain sufficient temperature with the evolution of combustible gas in each case due to overfluxing of transformer and the same gas may be collected in Buchholz Relay with consequent Alarm/Trip depending upon the quantity of gas collected which again depends upon the duration of time the transformer is subjected to overfluxing.

Due to **over fluxing in transformer** its core becomes saturated as such induced voltage in the primary circuit becomes more or less constant. If the supply voltage to the primary is increased to abnormal high value, there must be high magnetising current in the primary circuit.

Under such magnetic state of condition of transformer core linear relations between primary and secondary quantities (viz. for voltage and currents) are lost.

So there may not be sufficient and appropriate reflection of this high primary magnetising current to secondary circuit as such mismatching of primary currents and secondary currents is likely to occur, **causing differential relay to operate as we do not have overfluxing protection for sub-Stn. transformers.**

**Stipulated Withstand-Duration of Over Fluxing in Transformers**

Over fluxing in transformer has sufficient **harmful effect towards its life** which has been explained. As overfluxing protection is not generally provided in step-down transformers of Sub-Station, there must be a stipulated time which can be allowed matching with the transformer design to withstand such overfluxing without causing appreciable damage to the transformer and other protections shall be sensitive enough to trip the transformer well within such stipulated time, if cause of overfluxing is not removed by this time.
It is already mentioned that the flux density 'B' in transformer core is proportional to v/f ratio. Power transformers are designed to withstand \((V_n/f_n \times 1.1)\) continuously, where \(V_n\) is the normal highest r.m.s. voltage and \(f_n\) is the standard frequency. Core design is such that higher v/f causes higher core loss and core heating. The capability of a transformer to withstand higher v/f values i.e. overfluxing effect, is limited to a few minutes as furnished below in the Table

<table>
<thead>
<tr>
<th>(F = (V/f)/(V_n/f_n))</th>
<th>1.1</th>
<th>1.2</th>
<th>1.25</th>
<th>1.3</th>
<th>1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of withstand limit (minutes)</td>
<td>continuous</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
</tr>
</tbody>
</table>

From the table above it may be seen that when over fluxing due to system hazards reaches such that the factor \(F\) attains a values 1.4, the transformer shall be tripped out of service instantaneously otherwise there may be a permanent damage.

**Protection Against Over fluxing (v/f - Protection) in Transformer**

The condition arising out of overfluxing does not call for high speed tripping. Instantaneous operation is undesirable as this would cause tripping on momentary system disturbances which can be borne safely but the normal condition must be restored or the transformer must be isolated within one or two minutes at the most.

Flux density is proportional to V/f and it is necessary to detect a ratio of V/f exceeding unity, V and f being expressed in per unit value of rated quantities.

In a typical scheme designed for over fluxing protection, the system voltage as measured by the voltages transformer is applied to a resistance to produce a proportionate current; this current on being passed through a capacitor, produces a voltage drop which is proportional to the functioning in question i.e. V/f and hence to flux in the power transformer.

This is accompanied with a fixed reference D.C. voltage obtained across a Zener diode. When the peak A.C. signal exceeds the D.C. reference it triggers a transistor circuit which operates two electromechanical auxiliary elements. One is initiated after a fixed time delay, the other after an additional time delay which is adjustable.

The overfluxing protection operates when the ratio of the terminal voltage to frequency exceeds a predetermined setting and resets when the ratio falls below 95 to 98% of the operating ratio. By adjustment of a potentiometer, the setting is calibrated from 1 to 1.25 times the ratio of rated volts to rated frequency.
The output from the first auxiliary element, which operates after fixed time delay available between 20 to 120 secs. second output relay operates and performs the tripping function.

It is already pointed out that high V/f occur in Generator Transformers and Unit-Auxiliary Transformers if full exaltation is applied to generator before full synchronous speed is reached. V/f relay is provided in the automatic voltage regulator of generator. This relay blocks and prevents increasing excitation current before full frequency is reached.

When applying V/f relay to step down transformer it is preferable to connect it to the secondary (L.V. side of the transformer) so that change in tap position on the H.V. is automatically taken care of. Further the relay should initiate an Alarm and the corrective operation be done / got done by the operator. On extreme eventuality the transformer controlling breaker may be allowed to trip.

**Three Phase Transformer**

*Comparison between single Three Phase transformer and bank of three Single Phase transformers for three phase system*

It is found that generation, transmission and distribution of electrical power are more economical in three phase system than single phase system. For three phase system three single phase transformers are required. Three phase transformation can be done in two ways, by using single three phase transformer or by using a bank of three single phase transformers. Both are having some advantages over other. Single 3 phase transformer costs around 15% less than bank of three single phase transformers. Again former occupies less space than later. For very big transformer, it is impossible to transport large three phase transformer to the site and it is easier to transport three single phase transformers which is erected separately to form a three phase unit. Another advantage of using bank of three single phase transformers is that, if one unit of the bank becomes out of order, then the bank can be run as open delta.

**Connection of Three Phase Transformer**

A Varity of connection of three phase transformer are possible on each side of both a single 3 phase transformer or a bank of three single phase transformers.

**Marking or labeling the different terminals of transformer.**

Terminals of each phase of HV side should be labeled as capital letters, A, B, C, and those of LV side should be labeled as small letters, a, b, c. Terminal polarities are indicated by suffixes 1 & 2. Suffix 1’s indicate similar polarity ends and so do 2’s.
Star Star Transformer

Star Star Transformer is formed in a 3 phase transformer by connecting one terminal of each phase of individual side, together. The common terminal is indicated by suffix 1 in the figure below. If terminal with suffix 1 in both primary and secondary are used as common terminal, voltages of primary and secondary are in same phase. That is why this connection is called zero degree connection or $0^\circ$ - connection.

If the terminals with suffix 1 is connected together in HV side as common point and the terminals with suffix 2 in LV side are connected together as common point, the voltages in primary and secondary will be in opposite phase. Hence, Star Star Transformer connection is called $180^\circ$ - Connection, of three phase transformer.

Delta Detla Transformer

In delta delta transformer, 1 suffixed terminals of each phase primary winding will be connected with 2 suffixed terminal of next phase primary winding.
If primary is HV side, then A₁ will be connected to B₂, B₁ will be connected to C₂ and C₁ will be connected to A₂. Similarly in LV side 1 suffixed terminals of each phase winding will be connected with 2 suffixed terminals of next phase winding. That means, a₁ will be connected to b₂, b₁ will be connected to c₂ and c₁ will be connected to a₂. If transformer leads are taken out from primary and secondary 2 suffixed terminals of the winding, then there will be no phase difference between similar line voltages in primary and secondary. This delta delta transformer connection is zero degree connection or 0° - Connection.

But in LV side of transformer, if, a₂ is connected to b₁, b₂ is connected to c₁ and c₂ is connected to a₁. The secondary leads of transformer are taken out from 2 suffixed terminals of LV windings, and then similar line voltages in primary and secondary will be in phase opposition. This connection is called 180° - Connection, of three phase transformer.

**Star Delta Transformer**

Here in star delta transformer, star connection in HV side is formed by connecting all the 1 suffixed terminals together as common point and transformer primary leads are taken out from 2 suffixed terminals of primary windings.

The delta connection in LV side is formed by connecting 1 suffixed terminals of each phase LV winding with 2 suffixed terminal of next phase LV winding. More clearly, a₁ is connected to b₂, b₁ is connected to c₂ and c₁ is connected to a₂. The secondary (here it considered as LV) leads are taken out from 2 suffixed ends of the secondary windings of transformer. The transformer connection diagram is shown in the figure beside. It is seen from the figure that the sum of the voltages in delta side is zero. This is a must as otherwise closed delta would mean a short circuit. It is also observed from the phasor diagram that, phase to neutral voltage (equivalent star basis) on the delta side lags by – 30° to the phase to neutral voltage on the star side; this is also the phase relationship between the respective line to line voltages. This star delta transformer connection is therefore known as – 30° - Connection.
Star – Delta + 30° connection is also possible by connecting secondary terminals in following sequence. \( a_2 \) is connected to \( b_1 \), \( b_2 \) is connected to \( c_1 \) and \( c_2 \) is connected to \( a_1 \). The secondary leads of transformer are taken out from 2 suffixed terminals of LV windings,

![Diagram of Delta-Star Three Phase Transformer]

**Delta Star Transformer**

*Delta star transformer* connection of three phase transformer is similar to star – delta connection. If any one interchanges HV side and LV side of star – delta transformer in diagram, it simply becomes delta – star connected 3 phase transformer. That means all small letters of star delta connection should be replaced by capital letters and all small letters by capital in *delta star transformer* connection.

**Delta Zigzag Transformer**

The winding of each phase on the star connected side is divided into two equal halves in *delta zig zag transformer*. Each leg of the core of transformer is wound by half winding from two different secondary phases in addition to its primary winding.

**Star Zigzag Transformer**

The winding of each phase on the secondary star in a *star zigzag transformer* is divided into two equal halves. Each leg of the core of transformer is wound by half winding from two different secondary phases in addition to its primary winding.

**Choice between Star connection and Delta connection of Three Phase Transformer**

In star connection with earthed neutral, phase voltage i.e. phase to neutral voltage, is \( 1/\sqrt{3} \) times of line voltage i.e. line to line voltage. But in the case of delta connection phase voltage is equal to line voltage.
Star connected high voltage side electrical power transformer is about 10% cheaper than that of delta connected high voltage side transformer.

Let’s explain,

Let, the voltage ratio of transformer between HV & LV is K, voltage across HV winding is \( V_H \) and voltage across LV winding is \( V_L \) and voltage across transformer leads in HV side say \( V_p \) and in LV say \( V_s \).

**In Star Star Transformer**

\[
V_H = \frac{V_p}{\sqrt{3}} \quad \text{and} \quad V_L = \frac{V_s}{\sqrt{3}}
\]

\[
\Rightarrow \frac{V_p}{V_s} = \frac{V_H}{V_L} = K
\]

\[
\Rightarrow V_H = K \cdot V_L
\]

Voltage difference between HV & LV winding,

\[
V_H - V_L = V_p - V_s = (K - 1) \cdot V_s
\]

**In Star Delta Transformer**

\[
V_H = \frac{V_p}{\sqrt{3}} \quad \text{and} \quad V_L = V_s
\]

Voltage difference between HV & LV winding,

\[
V_H - V_L = \frac{V_p}{\sqrt{3}} - V_s = (K/\sqrt{3} - 1) \cdot V_s
\]

**In Delta Star Transformer**

\[
V_H = V_p \quad \text{and} \quad V_L = \frac{V_s}{\sqrt{3}}
\]

Voltage difference between HV & LV winding,

\[
V_H - V_L = V_p - \frac{V_s}{\sqrt{3}} = (K - 1/\sqrt{3}) \cdot V_s
\]

**For 132/33KV transformer \( K = 4 \)**

Therefore, case 1,

Voltage difference between HV & LV winding,

\[
(4 - 1) \cdot V_s = 3 \cdot V_s
\]

case 2,

Voltage difference between HV & LV winding,

\[
(4/\sqrt{3} - 1) \cdot V_s = 1.3 \cdot V_s
\]

and case 3,

Voltage difference between HV &
LV winding,
\[(4 - \sqrt[3]{3}) V_s = 3.42 V_s\]

In case 2 voltage difference between HV and LV winding is minimum therefore potential stresses between them is minimum, implies insulation cost in between these windings is also less.

Hence for step down purpose Star – Delta transformer connection is most economical, design for transformer. Similarly it can be proved that for Step up purpose Delta - Star three phase transformer connection is most economical.
Current Transformer

Definition of Instrument Transformer

Instrument transformers means current transformer & voltage transformer are used in electrical power system for stepping down currents and voltages of the system for metering and protection purpose. Actually relays and meters used for protection and metering, are not designed for high currents and voltages.

High currents or voltages of electrical power system cannot be directly fed to relays and meters. Current transformer steps down rated system current to 1 Amp or 5 Amp similarly voltage transformer steps down system voltages to 110V. The relays and meters are generally designed for 1 Amp, 5 Amp and 110V.

Definition of current transformer(CT)

A current transformer (CT) is an instrument transformer in which the secondary current is substantially proportional to primary current and differs in phase from it by ideally zero degree.

CT Accuracy Class or Current Transformer Class

A CT is similar to a electrical power transformer to some extent, but there are some difference in construction and operation principle. For metering and indication purpose, accuracy of ratio, between primary and secondary currents are essential within normal working range.

Normally accuracy of current transformer required upto 125% of rated current; as because allowable system current must be below 125% of rated current.

Rather it is desirable the CT core to be saturated after this limit since the unnecessary electrical stresses due to system over current can be prevented from the metering instrument connected to the secondary of the current transformer as secondary current does not go above a desired limit even primary current of the CT rises to a very high value than its ratings. So accuracy within working range is main criteria of a current transformer used for metering purpose.

The degree of accuracy of a Metering CT is expressed by CT Accuracy Class or simply Current Transformer Class or CT Class.
But in the case of protection, the CT may not have the accuracy level as good as metering CT although it is desired not to be saturated during high fault current passes through primary. So core of protection CT is so designed that it would not be saturated for long range of currents.

If saturation of the core comes at lower level of primary current the proper reflection of primary current will not come to secondary, hence relays connected to the secondary may not function properly and protection system loses its reliability.

Suppose you have one CT with current ratio 400/1A and its protection core is situated at 500A. If the primary current of the CT becomes 1000A the secondary current will still be 1.25A as because the secondary current will not increase after 1.25A because of saturation.

If actuating current of the relay connected the secondary circuit of the CT is 1.5A, it will not be operated at all even fault level of the power circuit is 1000A.

The degree of accuracy of a Protection CT may not be as fine as Metering CT but it is also expressed by CT Accuracy Class or simply Current Transformer Class or CT Class as in the case of Metering Current Transformer but in little bit different manner.
Theory of Current Transformer or CT

A current transformer functions with the same basic working principle of electrical power transformer, as we discussed earlier, but here is some difference. If a electrical power transformer or other general purpose transformer, primary current varies with load or secondary current. In case of current transformer, primary current is the system current and this primary current or system current transforms to the CT secondary, hence secondary current or burden current depends upon primary current of the current transformer.

Are you confused? OK let us clear you.

In a power transformer, if load is disconnected, there will be only magnetizing current flows in the primary. The primary of the power transformer takes current from the source proportional to the load connected with secondary.

But in case of Current transformer, the primary is connected in series with power line. So current through its primary is nothing but the current flows through that power line. The primary current of the CT, hence does not depend upon whether the load or burden is connected to the secondary or not or what is the impedance value of burden.

Generally current transformer has very few turns in primary where as secondary turns is large in number. Say \( N_p \) is number of turns in CT primary and \( I_p \) is the current through primary. Hence the primary AT is equal to \( N_pI_p \) AT.

If number of turns in secondary and secondary current in that CT are \( N_s \) and \( I_s \) respectively then Secondary AT is equal to \( N_sI_s \) AT.

In an ideal CT the primary AT is exactly is equal in magnitude to secondary AT.

So from the above statement it is clear that if a CT has one turn in primary and 400 turns in secondary winding, if it has 400 A current in primary then it will have 1A in secondary burden. Thus the turn ratio of the CT is 400/1A

Error in Current Transformer or CT

But in an actual current transformer, errors with which we are connected can best be considered through a study of phasor diagram for a CT,
Let us take flux as reference. EMF $E_s$ and $E_p$ lags behind the flux by 90°. The magnitude of the passers $E_s$ and $E_p$ are proportional to secondary and primary turns. The excitation current $I_o$ which is made up of two components $I_m$ and $I_w$. The secondary current $I_o$ lags behind the secondary induced emf $E_s$ by an angle $\Phi_s$. The secondary current is now transferred to the primary side by reversing $I_s$ and multiplied by the turns ratio $K_T$. The total current flows through the primary $I_p$ is then vector sum of $K_T I_s$ and $I_o$.

The Current Error or Ratio Error in Current Transformer or CT

From above passer diagram it is clear that primary current $I_p$ is not exactly equal to the secondary current multiplied by turns ratio, i.e. $K_T I_s$. This difference is due to the primary current is contributed by the core excitation current. The error in current transformer introduced due to this difference is called current error of CT or Current error of current transformer or some times Ratio Error in Current Transformer.

Hence, the percentage current error = \{\frac{|I_p| - |K_T I_s|}{|I_p|}\} \times 100\%
Phase Error or Phase Angle Error in Current Transformer

For an ideal current transformer the angle between the primary and reversed secondary current vector is zero. But for an actual current transformer there is always a difference in phase between two due to the fact that primary current has to supply the component of the exiting current. The angle between the above two phases is termed as Phase Angle Error in Current Transformer or CT. Here in the pharos diagram it is $\beta$ the phase angle error is usually expressed in minutes.

Cause of error in current transformer

The total primary current is not actually transformed in CT. One part of the primary current is consumed for core excitation and remaining is actually transformers with turns ratio of CT so there is error in current transformer means there are both Ratio Error in Current Transformer as well as a Phase Angle Error in Current Transformer.

How to reduce error in current transformer

It is desirable to reduce these errors, for better performance. For achieving minimum error in current transformer, one can follow the following,

1) Using a core of high permeability and low hysteresis loss magnetic materials.
2) Keeping the rated burden to the nearer value of the actual burden.
3) Ensuring minimum length of flux path and increasing cross – sectional area of the core, minimizing joint of the core.
4) Lowering the secondary internal impedance.
Voltage Transformer or Potential Transformer

Potential Transformer Definition

Potential Transformer or Voltage Transformer are used in electrical power system for stepping down the system voltage to a safe value which can be fed to low ratings meters and relays. Commercially available relays and meters used for protection and metering, are designed for low voltage. This is a simplest form of Potential Transformer Definition

Voltage Transformer or Potential Transformer Theory

A Voltage Transformer theory or Potential Transformer theory is just like theory of general purpose step down transformer. Primary of this transformer is connected across the phases or and ground depending upon the requirement. Just like the transformer, used for stepping down purpose, potential transformer i.e. PT has lowers turns winding at its secondary. The system voltage is applied across the terminals of primary winding of that transformer, and then proportionate secondary voltage appears across the secondary terminals of the PT.

The secondary voltage of the PT is generally 110V. In an ideal Potential Transformer or Voltage Transformer when rated burden connected across the secondary the ratio of primary and secondary voltages of transformer is equal to the turns ratio and furthermore the two terminal voltages are in precise phase opposite to each other. But in actual transformer there must be an error in the voltage ratio as well as in the phase angle between primary and secondary voltages.

The errors in Potential Transformer or Voltage Transformer can best be explained by phasor diagram, and this is the main part of Potential Transformer theory
Error in PT or Potential Transformer or VT or Voltage transformer

- **I_s** - Secondary Current
- **E_s** - Secondary induced emf
- **V_s** - Secondary terminal voltage
- **R_s** - Secondary winding resistance
- **X_s** - Secondary winding reactance
- **I_p** - Primary current
- **E_p** - primary induced emf
- **V_p** - Primary terminal voltage
- **R_p** - Primary winding resistance
- **X_p** - Primary winding reactance
- **K_T** - turns ratio = numbers of primary turns/number of secondary turns
- **I_o** - Excitation Current
- **I_m** - magnetizing component of I_o
- **I_w** - core loss component of I_o
- **Φ_m** - main flux
- **β** - phase angle error
As in the case of Current Transformer and other purpose Electrical Power Transformer, total primary current $I_p$ is the vector sum of excitation current and the current equal to reversal of secondary current multiplied by the ratio $1/K_T$

$$I_p = I_o + I_s/K_T$$

If $V_p$ is the system voltage applied to the primary of the PT then voltage drops due to resistance and reactance of primary winding due to primary current $I_p$ will comes into picture. After subtracting this voltage drop from $V_p$, $E_p$ will appear across the primary terminals. this $E_p$ is equal to primary induced emf. This primary emf will transform to the secondary winding by mutual induction and transformed emf is $E_s$. Again this $E_s$ will be dropped by secondary winding resistance and reactance, and resultant will actually appear across the burden terminals and it is denoted as $V_s$

So if system voltage is $V_p$, ideally $V_p/K_T$ should be the secondary voltage of PT, but in reality actual secondary voltage of PT is $V_s$.

**Voltage Error or Ratio Error in Potential Transformer (PT) or Voltage Transformer (VT)**

The difference between the ideal value $V_p/K_T$ and actual value $V_s$ is the voltage error or ratio error in a potential transformer, it can be expressed as ,

Percentage voltage error = $\left\{ (V_p - K_T.V_s)/V_p \right\} \times 100\%$

**Phase error or phase angle error in potential or voltage transformer**

The angle '$\beta'$ between the primary system voltage $V_p$ and the reversed secondary voltage vectors $K_T.V_s$ is the phase error.

**Cause of error in Potential Transformer**

The voltage applied to the primary of the potential transformer first drops due to internal impedance of primary. Then it appears across the primary winding and then transformed proportionally to its turns ratio, to secondary winding. This transformed voltage across secondary winding will again drops due to internal impedance of secondary, before appearing across burden terminals. This is the reason of errors in potential transformer.
Accuracy Limit Factor and Instrument Security Factor of CT or Current Transformer

Before understanding **Accuracy Limit Factor** and **Instrument Security Factor of CT or Current Transformer** we must try to understand different Technical Parameters of Instrument Transformer i.e. of **Current Transformer** and **Voltage Transformer**.

**Technical Parameters of Instrument Transformer**

Following are some of the normally used terms associated with Instrument Transformer, that is, both for **Current Transformer** and **Voltage Transformer**.

**Rated Primary Current of Current Transformer**

This is the value of rated primary current of Current Transformer on which the CT is designed to perform best. **Hence rated primary current of Current Transformer is an optimum value of primary current at which, error of the CT are minimum and losses in the CT are also less, that means in few words, performance of the CT is best; with optimum heating of the transformer**

**Rated Secondary Current of Current Transformer**

Like rated primary current, this is the value of secondary current due to which errors in the CT are minimum. In other words, **Rated Secondary Current of Current Transformer is the value of secondary current on which the best performance of the CT is based**

**Rated Burden of Current Transformer**

Whatever is connected externally with the secondary of a Current Transformer is called **burden of Current Transformer**. In **Electrical Power Transformer** the secondary is connected with load, but in case of **Current Transformer**, electrical consumer load is not connected to the secondary. In **Electrical Power Transformer** we loaded the secondary of the transformer by connecting consumer's one by one to the secondary side.

But in case of Current Transformer or other Instrument Transformer, we connect, metering instrument and protection relays to the secondary, which obviously behave like load of the Instrument Transformer but do not have any direct relation with the load of the **electrical power system**. That is why, all the instruments, wires etc connected with the secondary of the Instrument Transformer or IT is called burden rather load.
In this way, we distinguish the secondary circuit of a current transformer or voltage transformer from other purpose electrical transformer. Although literally, load and burden carry nearly same meaning in English Language.

**Rated burden of Current Transformer** is the value of the burden to be connected with the secondary of CT including connecting load resistance expressed in VA or ohms on which accuracy requirement is based.

Similarly Rated **burden of Voltage Transformer** is the value of the burden to be connected with the secondary of Voltage Transformer including connecting load resistance expressed in VA or ohms on which accuracy requirement is based.

**Rated Frequency of Current Transformer**

The value of the system frequency on which the **instrument transformer** operates.

**Accuracy Class of Current transformer**

There is always some difference in expected value and actual value of output of an instrument transformer Current Error and Phase Angle Error count in CT, as because primary current of current transformer has to contribute the excitation component of CT core.

**Accuracy class of current transformer** is the highest permissible percentage composite error at rated current.

The standard accuracy classes of current transformer as per IS - 2705 are 0.1, 0.2, 0.5, 1, 3 & 5 for metering CT

The accuracy class or simply class of measuring **current transformer** is 0.1, means the maximum permissible limit of error is 0.1%, more clearly, if we try to measure 100A with a 0.1 class CT, the measured value may be either 100.1 or 99.9 A or anything in between these range.

The standard accuracy class for the protection **current transformer**, as per IS 2705 are 5P, 10P, 15P.

Here in the protection **Current Transformer**, 5P means 5% 10P means 10% and 15P means 15% error and 'P' stands for Protection.
Limits of error in Current Transformers

Class 0.1 to 1.0: The Current Error and phase displacement Error at the rated frequency shall not exceed the values given below when the secondary burden is any value from 25% to 100% of the rated burden.

<table>
<thead>
<tr>
<th>Class</th>
<th>Limit of % error at % of rated current</th>
<th>Limit of % error at % of rated current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>0.1</td>
<td>± 0.25</td>
<td>± 0.2</td>
</tr>
<tr>
<td>0.2</td>
<td>± 0.50</td>
<td>± 0.35</td>
</tr>
<tr>
<td>0.5</td>
<td>± 1</td>
<td>± 0.75</td>
</tr>
<tr>
<td>1.0</td>
<td>± 2</td>
<td>± 1.5</td>
</tr>
</tbody>
</table>

Application of CT core according to their class

<table>
<thead>
<tr>
<th>Application</th>
<th>Accuracy Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As per IS</td>
</tr>
<tr>
<td>Precession Metering</td>
<td>0.1 or 0.2</td>
</tr>
<tr>
<td>Commercial Metering</td>
<td>0.5 or 1.0</td>
</tr>
<tr>
<td>Ammeters</td>
<td>1 or 3</td>
</tr>
<tr>
<td>Protection Relays</td>
<td>5P10 or 5P20</td>
</tr>
<tr>
<td>Special Protection</td>
<td>PS</td>
</tr>
</tbody>
</table>

Rated Short Circuit Current of a Current Transformer

In some abnormal condition like huge short circuit fault, the Current Transformer faces a huge current, flows through the CT primary. Although this fault current will not continue for long time as because every fault in the system is cleared by electrical protection system within very short time.

So Current Transformer should be designed in such a way that it can withstand this huge fault current at least for certain amount of time. It is unnecessary to design any equipment for withstanding short circuit current for long period of time since the short circuit fault is cleared by protection switch gear within fraction of second.
For CT rated Short Circuit Current of Current Transformer is defined as the rms value of primary current which the CT will withstand for a rated time with its secondary winding short circuited without suffering harmful effects.

**Rated Voltage for Current Transformer (CT)**

The RMS value of the voltage used to designate the CT for a particular highest system voltage is rated Voltage for Current Transformer. The voltage of electrical power system is increased if load of the system is reduced. As per standard, the system voltage can be raised up to 10% above the normal voltage during no load condition. So every electrical equipment is such designed so that it can withstand this highest voltage. As current transformer is an electrical equipment, it should also be designed to withstand highest system voltage.

**Instrument Security Factor**

ISF or Instrument Security Factor of current transformer is defined as the ratio of instrument limit primary current to the rated primary current. The instrument limit primary current of metering CT is the value primary current beyond which CT core becomes saturated.

**Accuracy Limit Factor**

For protection current transformer, the ratio of accuracy limit primary current to the rated primary current is called Accuracy Limit Factor of current transformer.

**Knee Point Voltage of Current Transformer**

Knee Point Voltage of Current Transformer is significance of saturation level of a current transformer core mainly used for protection purposes. The sinusoidal voltage of rated frequency is applied to the secondary terminals of CT, with other winding being open circuited which increased by 10%, cause the exiting current to increase by 50%.

**Current Transformer PS Class**

Before understanding Knee Point Voltage of Current Transformer and Current Transformer PS Class we should recall the terms Instrument Security Factor of CT and Accuracy Limit Factor.

**Instrument Security Factor or ISF of Current Transformer**

Instrument Security Factor is the ratio of Instrument Limit Primary Current to the rated Primary Current. Instrument Limit Current of a metering Current Transformer is the maximum value of primary current beyond which Current Transformer core becomes
saturated. **Instrument Security Factor of CT** is the significant factor for choosing the metering Instruments which to be connected to the secondary of the CT. Security or Safety of the measuring unit is better, if ISF is low. If we go through the example below it would be clear to us.

Suppose one Current Transformer has rating 100/1A and ISF is 1.5 and another Current Transformer has same rating with ISF 2.

That means, in first CT, the metering core would be saturated at 1.5X100 or 150 A, whereas is second CT, core will be saturated at 2X100 or 200A. That means whatever may be the primary current of both CTs, secondary current will not increase further after 150 & 200A of primary current of the CTs respectively. Hence maximum secondary current of the CTs would be 1.5 & 2.0 A.

As the maximum current can flow through the instrument connected to the first CT is 1.5A which is less than the maximum value of current can flow through the instrument connected to the second CT i.e. 2A. Hence security or safety of the instruments of first CT is better than later.

**Another significance of ISF is during huge electrical fault, the short circuit current, flows through primary of the CT does not affect destructively, the measuring instrument attached to it as because, the secondary current of the CT will not rise above the value of rated secondary current multiplied by ISF**

**Accuracy limit Factor or ALF of Current Transformer**

For protection current transformer, the ratio of accuracy limit primary current to the rated primary current.

\[
\text{Accuracy Limit Primary Current} = \frac{\text{ALF}}{\text{Rated Primary Current}}
\]

First we will explain, what is rated accuracy limit primary current?

Broadly, this is the maximum value of primary current, beyond which core of the protection CT or simply protection core of of a CT starts saturated. The value of rated accuracy limit primary current is always many times more than the value of instrument limit primary current.
Actually CT transforms the fault current of the electrical power system for operation of the protection relays connected to the secondary of that CT. If the core of the CT becomes saturated at lower value of primary current, as in the case of metering CT, the system fault will not reflect properly to the secondary, which may cause, the relays remain inoperative even the fault level of the system is large enough.

That is why the core of the protection CT is made such a way that saturation level of that core must be high enough. But still there is a limit as because, it is impossible to make one magnetic core with infinitely high saturation level and secondly most important reason is that although the protection care should have high saturation level but that must be limited up to certain level otherwise total transformation of primary current during huge fault may badly damage the protection relays.

So it is clear from above explanation, rated accuracy limit primary current, should not be so less, that it will not at all help the relays to be operated on the other hand this value must not be so high that it can damage the relays.

So, Accuracy Limit Factor or ALF should not have the value nearer to unit and at the same time it should not be as high as 100. The standard values of ALF as per IS - 2705 are 5,10, 15, 20 & 30.

**Knee Point Voltage of Current Transformer**

This is the significance of saturation level of a CT core mainly used for protection purposes. The sinusoidal voltage of rated frequency applied to the secondary terminals of Current Transformer, with other winding being open circuited, which when increased by 10% cause the exiting current to increase 50%. The CT core is made of CRGO steel. It has its own saturation level.

The EMF induced in the CT secondary windings is

\[ E_2 = 4.44\phi fT_2 \]

Where, \( f \) is the system frequency, \( \phi \) is the maximum magnetic flux in Wb. \( T_2 \) is the number of turns of the secondary winding. The flux in the core, is produced by excitation current \( I_e \).

We have a non - liner relationship between excitation current and magnetizing flux. After certain value of excitation current, flux will not further increase so rapidly with increase in excitation current. this non-liner relation curve is also called B - H curve.

Again from the equation above, it is found that, secondary voltage of a Current Transformer is directly proportional to flux \( \phi \). Hence one typical curve can be drawn from this relation between secondary voltage and excitation current as shown below,
It is clear from the curve that, Linear relation between \( V \) & \( I_e \) is maintained from point A & K. The point 'A' is known as 'Ankle Point' and point 'K' is known as 'Knee Point'.

\[
\begin{align*}
\text{Saturation Curve of CT Core} \\
\text{V} & \quad \text{VK} \\
A & \quad \text{VK/2} \\
O & \quad \text{Ie at VK/2} \\
\end{align*}
\]

In Differential and Restricted Earth Fault (REF) protection scheme, accuracy class and ALF of the CT may not ensure the reliability of the operation. It is desired that, Differential and REF relays should not be operated when fault occurs outside the protected transformer.

When any fault occurs outside the Differential Protection zone, the faulty current flows through the CTs of both sides of Electrical Power Transformer. The both LV & HV CTs have magnetizing characteristics.

Beyond the Knee Point, for slight increase in secondary emf a large increasing in excitation current is required. So after this knee point excitation current of both Current Transformers will be extremely high, which may cause mismatch between secondary current of LV & HV Current Transformers. This phenomena may cause unexpected tripping of Power Transformer.

So the magnetizing characteristics of both LV & HV sides CTs, should be same that means they have same knee point voltage \( V_k \) as well as same excitation current \( I_e \) at \( V_{k/2} \). It can be again said that, if both knee point voltage of current transformer and magnetizing characteristic of CTs of both sides of Power Transformer differ, there must be a mismatch in high excitation currents of the CTs during fault which ultimately causes the unbalancing between secondary current of both groups of CTs and transformer trips.

So for choosing CT for Differential Protection of Transformer, one should consider Current Transformer PS Class rather its conventional protection class. PS stands for protection Special which is defined by Knee Point voltage of current transformer \( V_k \) and excitation current \( I_e \) at \( V_{k/2} \).
Why CT secondary should not be kept open

The electrical power system load current always flows through current transformer primary; irrespective of whether the Current Transformer is open circuited or connected to burden at its secondary.

If CT secondary is open circuited, all the primary current will behave as excitation current, which ultimately produce huge voltage.

Every Current Transformer has its own Non - Linear magnetizing curve, because of which secondary open circuit voltage should be limited by saturation of the core. If one can measure the rms voltage across the secondary terminals, he or she will get the value which may not appear to be dangerous. As the CT primary current is sinusoidal in nature, it zeros 100 times per second.(As frequency of the current is 50Hz). The rate of change of flux at every current zero is not limited by saturation and is high indeed. This develops extremely high peaks or pulses of voltage. This high peaks of voltage may not be measured by conventional voltmeter. But these high peaks of induced voltage may breakdown the CT insulation, and may case accident to personnel. The actual open - circuit voltage peak is difficult to measure accurately because of its very short peaks. That is why CT secondary should not be kept open.
Earthing Transformer or Grounding Transformer

Stability on External Earth Fault (E/F) on Delta Side of Y/Δ Power Transformer

If the earthing transformer on the Delta Side is outside the Zone of protection the Earth Fault(E/F) in the delta system outside Current Transformer(CT) locations would produce current distributions as shown which circulate within the differential CT secondaries and is kept out of operating coils.

Zig-Zag or inter connected star grounding transformer has normal magnetising impedance of high value but for E/F, currents flow in windings of the same - core in such a manner that the ampere turns cancel and hence offer lower impedance.

In cases where the neutral point of three phase system is not accessible like the system connected to the delta connected side of a electrical power transformer, an artificial neutral point may be created with help of a zigzag connected earthing transformer.

This is a core type transformer with three limbs. Every phase winding in zigzag connection is divided into two equal halves. One half of which is wound on one limb and other half is wound on another limb of the core of transformer.

1st half of Red phase winding is wound on the 1st limb of the core and 2nd half of same Red phase is wound on 3rd limb.

1st half of Yellow phase winding is wound on the 2nd limb of the core and 2nd half of same Yellow phase is wound on 1st limb.

1st half of Blue phase winding is wound on the 3rd limb of the core and 2nd half of same Blue phase is wound on 2nd limb.
End point of all three windings ultimately connected together and forms a common neutral point.

Now if any fault occurs at any of the phases in delta connected system, the zero sequence fault current has close path of circulating through earth as shown in the figure.

In normal condition of the system, the voltage across the winding of the earthing transformer is \( \frac{1}{\sqrt{3}} \) times of rated per phase voltage of the system.

But when single line to ground fault occurs on any phase of the system, as shown in the figure, zero sequence component of the earth fault current flows in the earth and returns to the electrical power system by way of earth star point of the earthing transformer.

It gets divided equally in all the three phases. Hence, as shown in the figure, the currents in the two different halves of two windings in the same limb of the core flow in opposite directions. And therefore the magnetic flux set up by these two currents will oppose and neutralize each other.

. As there is no increase in flux due to fault current, there is no extra \( \frac{d\phi}{dt} \) means no extra voltage induced across the winding and no choking effect occurs to impede the flow of fault current. So it can be concluded like that, the zigzag type earthing or grounding transformer maintains the rated supply voltage at normal current as well as when a solid single line to ground fault current flows through it.

The rated voltage of an earthing or grounding transformer is the line to line voltage on which it is intended to be used.

Current rating of this transformer is the maximum neutral current in Amperes that the transformer is designed to carry in fault condition for a specific time. Generally the time interval, for which transformer designed to carry the maximum fault current through it safely, is taken as 30 second.
**External and Internal Faults in Power Transformer**

This is essential to protect high value transformer against external and internal electrical faults.

**External Faults in Power Transformer**

**External Short - Circuit of Power Transformer**

The short - circuit may occurs in two or three phases of electrical power system. The level of fault current is always high enough. It depends upon the voltage which has been short - circuited and upon the impedance of the circuit up to the fault point. The copper loss of the fault feeding transformer is abruptly increased. This increasing copper loss causes internal heating in the transformer. Large fault current also produces severe mechanical stresses in the transformer. The maximum mechanical stresses occurs during first cycle of symmetrical fault current.

**High Voltage Disturbance in Power Transformer**

High Voltage Disturbance in Power Transformer are of two kinds,

(1) Transient Surge Voltage

(2) Power Frequency Over Voltage

**Transient Surge Voltage**

High voltage and high frequency surge may arise in the power system due to any of the following causes,

(a) Arcing ground if neutral point is isolated.

(b) Switching operation of different electrical equipment.

(c) Atmospheric Lightening Impulse.

Whatever may be the causes of surge voltage, it is after all a travelling wave having high and steep wave form and also having high frequency. This wave travels in the electrical power system network, upon reaching in the power transformer, it causes breakdown the insulation between turns adjacent to line terminal, which may create short circuit between turns.
**Power Frequency Over Voltage**

There may be always a chance of system over voltage due to sudden disconnection of large load. *Although the amplitude of this voltage is higher than its normal level but frequency is same as it was in normal condition.*

Over voltage in the system causes an increase in stress on the insulation of transformer. As we know that, voltage $V = 4.44\Phi f T \Rightarrow V \propto \Phi$, increased voltage causes proportionate increase in the working flux.

This therefore causes, increased in iron loss and disproportionately large increase in magnetizing current. The increase flux is diverted from the transformer core to other steel structural parts of the transformer. Core bolts which normally carry little flux, may be subjected to a large component of flux diverted from saturated region of the core alongside. Under such condition, the bolt may be rapidly heated up and destroys their own insulation as well as winding insulation.

**Under Frequency effect in Power Transformer**

As, voltage $V = 4.44\Phi f T \Rightarrow V \propto \Phi f$ as the number of turns in the winding is fixed.

Therefore, $\Phi \propto V/f$

From, this equation it is clear that if frequency reduces in a system, the flux in the core increases, the effect are more or less similar to that of the over voltage.

**Internal Faults in Power Transformer**

The principle faults which occurs inside a power transformer are categorized as,

1. Insulation breakdown between winding and earth
2. Insulation breakdown in between different phases
3. Insulation breakdown in between adjacent turns i.e. inter-turn fault
4. Transformer core fault
**Internal Earth Faults in Power Transformer**

**Internal Earth Faults in a Star connected winding with neutral point earthed through impedance**

In this case the fault current is dependent on the value of earthing impedance and is also proportional to the distance of the fault point from neutral point as the voltage at the point depends upon, the number of winding turns come under across neutral and fault point.

If the distance between fault point and neutral point is more, the number of turns come under this distance is also more, hence voltage across the neutral point and fault point is high which causes higher fault current.

So, in few words it can be said that, the value of fault current depends on the value of earthing impedance as well as the distance between the faulty point and neutral point.

The fault current also depends up on leakage reactance of the portion of the winding across the fault point and neutral. But compared to the earthing impedance, it is very low and it is obviously ignored as it comes in series with comparatively much higher earthing impedance.

**Internal Earth Faults in a Star connected winding with neutral point solidly earthed**

In this case, earthing impedance is ideally zero. The fault current is dependent up on leakage reactance of the portion of winding comes across faulty point and neutral point of transformer. The fault current is also dependent on the distance between neutral point and fault point in the transformer.

As said in previous case the voltage across these two points depends upon the number of winding turn comes across faulty point and neutral point. So in star connected winding with neutral point solidly earthed, the fault current depends upon two main factors, first the leakage reactance of the winding comes across faulty point and neutral point and secondly the distance between faulty point and neutral point.

But the leakage reactance of the winding varies in complex manner with position of the fault in the winding.

It is seen that the reactance decreases very rapidly for fault point approaching the neutral and hence the fault current is highest for the fault near the neutral end. So at this point, the voltage available for fault current is low and at the same time the reactance opposes the fault current is also low, hence the value of fault current is high enough.

Again at fault point away from the neutral point, the voltage available for fault current is high but at the same time reactance offered by the winding portion between fault point and neutral point is high. It can be noticed that the fault current stays a very high level.
throughout the winding. In other word, the fault current maintain a very high magnitude irrelevant to the position of the fault on winding.

**Internal Phase to Phase Faults in Power Transformer**

Phase to phase fault in the transformer are **rare**. If such a fault does occur, it will give rise to substantial current to **operate instantaneous over current relay on the primary side** as well as the **differential relay**.

**Inter turns fault in Power Transformer**

Power Transformer connected with electrical extra high voltage transmission system, is very likely to be subjected to high magnitude, steep fronted and high frequency impulse voltage due to lightening surge on the transmission line. The voltage stresses between winding turns become so large, it can not sustain the stress and causing insulation failure between inter - turns in some points. Also LV winding is stressed because of the transferred surge voltage.

**Very large number of Power Transformer failure arise from fault between turns.**

**Inter turn fault may also be occured due to mechanical forces between turns originated by external short circuit.**

**Core fault in Power Transformer**

In any portion of the core lamination is damaged, or lamination of the core is bridged by any conducting material causes sufficient eddy current to flow, hence, this part of the core becomes over heated.

Some times, insulation of bolts (Used for tightening the core lamination together) fails which also permits sufficient eddy current to flow through the bolt and causing over heating.

These insulation failure in lamination and core bolts causes severe local heating. Although these local heating, causes additional core loss but cannot create any noticeable change in input and output current in the transformer, hence these faults cannot be detected by normal electrical protection scheme.

This is desirable to detect the local over heating condition of the transformer core before any major fault occurs.

Excessive over heating leads to breakdown of transformer insulating oil with evolution of gases. These gases are accumulated in Buchholz relay and actuating Buchholz Alarm.
Backup Protection of Transformer

Over Current and Earth Fault Protection of Transformer

Backup protection of electrical transformer is simple Over Current and Earth Fault protection applied against external short circuit and excessive over loads. These over current and earth Fault relays may be of Inverse Definite Minimum Time (IDMT) or Definite Time type relays.

Generally IDMT relays are connected to the in-feed side of the transformer. The over current relays cannot distinguish between external short circuit, over load and internal faults of the transformer.

For any of the above fault, backup protection i.e. over current and earth fault protection connected to in-feed side of the transformer will operate. Backup protection is although generally installed at in feed side of the transformer, but it should trip both the primary and secondary circuit breakers of the transformer.

Over Current and Earth Fault protection relays may be also provided in load side of the transformer too, but it should not inter trip the primary side Circuit Breaker like the case of backup protection at in-feed side.

The operation is governed primarily by current and time settings and the characteristic curve of the relay. To permit use of over load capacity of the transformer and co-ordination with other similar relays at about 125 to 150% of full load current of the transformer but below the minimum short circuit current.

Backup protection of transformer has four elements, three over current relays connected each in each phase and one earth fault relay connected to the common point of three over current relays as shown in the figure. The normal range of current settings available on IDMT over current relays is 50% to 200% and on earth fault relay 20 to 80%.
Star-connected winding

Backup O/C & E/F Protection Scheme

Delta-connected winding

Backup O/C & E/F Protection Scheme

Star-connected winding

O/C & Unrestricted E/F Protection Scheme
Another range of setting on earth fault relay is also available and may be selected where the earth fault current is restricted due to insertion of impedance in the neutral grounding. In the case of transformer winding with neutral earthed, unrestricted earth fault protection is obtained by connecting an ordinary earth fault relay across a neutral current transformer.

The unrestricted over current and earth fault relays should have proper time lag to co-ordinate with the protective relays of other circuit to avoid indiscriminate tripping

**Differential Protection of Transformer**

Generally **Differential protection** is provided in the **electrical power transformer** rated **more than 5MVA**. The **Differential Protection of Transformer** has many advantages over other schemes of protection.

1) The faults occur in the transformer inside the insulating oil can be detected by Buchholz relay. But if any fault occurs in the transformer but not in oil then it cannot be detected by Buchholz relay. Any flash over at the bushings are not adequately covered by Buchholz relay. **Differential relays** can detect such type of faults.

   Moreover Buchholz relay is provided in transformer for detecting any internal fault in the transformer but Differential Protection scheme detects the same in faster way.

2) The **differential relays** normally response to those faults which occur in side the differential protection zone of transformer.

**Differential Protection Scheme in a Power Transformer**

**Principle of Differential Protection**

Principle of **Differential Protection** scheme is one simple conceptual technique.

The differential relay actually compares between primary current and secondary current of power transformer, if any unbalance found in between primary and secondary currents the relay will actuate and inter trip both the primary and secondary circuit breaker of the transformer.

Suppose you have one transformer which has primary rated current $I_p$ and secondary current $I_s$. If you install CT of ratio $I_p/1A$ at primary side and similarly, CT of ratio $I_s/1A$ at secondary side of the transformer.
The secondaries of these both CTs are connected together in such a manner that secondary currents of both CTs will oppose each other.

In other words, the secondaries of both CTs should be connected to same current coil of differential relay in such a opposite manner that there will be no resultant current in that coil in normal working condition of the transformer.

But if any major fault occurs inside the transformer due to which the normal ratio of the transformer disturbed then the secondary current of both transformer will not remain the same and one resultant current will flow through the current coil of the differential relay, which will actuate the relay and inter trip both the primary and secondary circuit breakers.

To correct phase shift of current because of star - delta connection of transformer winding in case of three phase transformer, the current transformer secondaries should be connected in delta and star as shown here.

At maximum through fault current, the spill output produced by the small percentage unbalance may be substantial. Therefore, differential protection of transformer should be provided with a proportional bias of an amount which exceeds in effect the maximum ratio deviation.
Restricted Earth Fault Protection

Restricted Earth Fault Protection of Transformer

An external fault in the star side will result in current flowing in the line current transformer of the affected phase and at the same time a balancing current flows in the neutral current transformer, hence the resultant current in the relay is therefore zero. So this REF relay will not be actuated for external earth fault.

But during internal fault the neutral current transformer only carries the unbalance fault current and operation of Restricted Earth Fault Relay takes place.

This scheme of restricted earth fault protection is very sensitive for internal earth fault of electrical power transformer. The protection scheme is comparatively cheaper than differential protection scheme.

Restricted earth fault protection is provided in electrical power transformer for sensing internal earth fault of the transformer.

In this scheme the CT secondary of each phase of electrical power transformer are connected together as shown in the figure. Then common terminals are connected to the secondary of a Neutral Current Transformer or NCT.

The CT or Current Transformer connected to the neutral of power transformer is called Neutral Current Transformer or Neutral CT or simply NCT.

Whenever there is an unbalancing in between three phases of the power transformer, a resultant unbalance current flow through the close path connected to the common terminals of the CT secondaries.

An unbalance current will also flow through the neutral of power transformer and hence there will be a secondary current in Neutral CT because of this unbalance neutral current.

In Restricted Earth Fault scheme the common terminals of phase CTs are connected to the secondary of Neutral CT in such a manner that secondary unbalance current of phase CTs and the secondary current of Neutral CT will oppose each other.

If these both currents are equal in amplitude there will not be any resultant current circulate through the said close path. The Restricted Earth Fault Relay is connected in this close path. Hence the relay will not response even there is an unbalancing in phase current of the power transformer.
Restricted E/F Protection Scheme with O/C

Restricted E/F Protection Scheme

Restricted E/F Protection for Star Winding
**Buchholz Relay in transformer**

**What is Buchholz Relay?**

**Construction of Buchholz Relay**

*Buchholz Relay in transformer* is an oil container housed the connecting pipe from main tank to conservator tank. It has mainly two elements.

The upper element consists of a float. The float is attached to a hinge in such a way that it can move up and down depending upon the oil level in the *Buchholz Relay* Container. One mercury switch is fixed on the float. The alignment of mercury switch hence depends upon the position of the float.

The lower element consists of a baffle plate and mercury switch. This plate is fitted on a hinge just in front of the inlet (main tank side) of *Buchholz Relay in transformer* in such a way that when oil enters in the relay from that inlet in high pressure the alignment of the baffle plate along with the mercury switch attached to it, will change. In addition to these main elements a *Buchholz Relay* has gas release pockets on top. The electrical leads from both mercury switches are taken out through a molded terminal block.

**Buchholz Relay principle**

The *Buchholz Relay working principle* of is very simple. *Buchholz Relay function* is based on very simple mechanical phenomenon. It is mechanically actuated.

Whenever there will be a minor internal fault in the transformer such as an insulation faults between turns, break down of *core of transformer*, core heating, the *transformer insulating oil* will be decomposed in different hydrocarbon gases, CO$_2$ and CO.

The gases produced due to decomposition of transformer insulating oil will accumulate in the upper part the *Buchholz Container* which causes fall of oil level in it.

Fall of oil level means lowering the position of float and thereby tilting the mercury switch. The contacts of this mercury switch are closed and an alarm circuit energized. Sometime due to oil leakage on the main tank air bubbles may be accumulated in the upper part the *Buchholz Container* which may also cause fall of oil level in it and alarm circuit will be energized.

By collecting the accumulated gases from the gas release pockets on the top of the relay and by analyzing them one can predict the type of fault in the transformer.

More severe types of faults, such as short circuit between phases or to earth and faults in the tap changing equipment, are accompanied by a surge of oil which strikes the baffle plate and causes the mercury switch of the lower element to close.
This switch energized the trip circuit of the Circuit Breakers associated with the transformer and immediately isolate the faulty transformer from the rest of the electrical power system by inter tripping the Circuit Breakers associated with both LV and HV sides of the transformer. This is how Buchholz Relay functions.

**Buchholz Relay Operation – Certain Precaution**

The Buchholz Relay operation may be actuated without any fault in the transformer. For instance, when oil is added to a transformer, air may get in together with oil, accumulated under the relay cover and thus cause a false Buchholz Relay operation. That is why mechanical lock is provided in that relay so that one can lock the movement of mercury switches when oil is topping up in the transformer. This mechanical locking also helps to prevent unnecessary movement of breakable glass bulb of mercury switches during transportation of the Buchholz Relays.
The lower float may also falsely operate if the oil velocity in the connection pipe through, not due to internal fault, is sufficient to trip over the float. This can occurs in the event of external short circuit when over currents flowing through the winding cause overheated the copper and the oil and cause the oil to expand.

**Transformer Testing**

For confirming the specifications and performances of an electrical transformer it has to go through numbers of testing procedures. Some tests are done at manufacturer premises before delivering the transformer. Mainly two types of transformer testing are done at manufacturer premises - type test of transformer and routine test of transformer. In addition to that some transformer tests are also carried out at the consumer site before commissioning and also periodically in regular & emergency basis through out its service life.

**Type of transformer testing**

**Tests done at Factory**

- Type Tests
- Routine Tests
- Special Tests

**Tests done at Site**

- Pre Commissioning Tests
- Periodic/Condition Monitoring Tests
- Emergency Tests

**Type test of transformer**

To prove that the transformer meets customer’s specifications and design expectations, the transformer has to go through different testing procedures in manufacturer premises. Some transformer tests are carried out for confirming the basic design expectation of that transformer.

These tests are done mainly in a prototype unit not in all manufactured units in a lot. **Type test of transformer** confirms main and basic design criteria of a production lot.
Routine tests of transformer

Routine tests of transformer is mainly for confirming operational performance of individual unit in a production lot.

Routine tests are carried out on every unit manufactured.

Special tests of transformer

Special tests of transformer is done as per customer requirement to obtain information useful to the user during operation or maintenance of the transformer.

Pre commissioning test of transformer

In addition to these, the transformer also goes through some other tests, performed on it, before actual commissioning of the transformer at site. The transformer testing performed before commissioning the transformer at site is called pre commissioning test of transformer. These tests are done to assess the condition of transformer after installation and compare the test results of all the low voltage tests with the factory test reports.

Type tests of transformer includes

Transformer winding resistance measurement
Measurement of voltage ratio and check of voltage vector relationship
Measurement of impedance voltage/short circuit impedance (principal tap) and load loss (Short circuit test)
Measurement of no load loss and current (Open circuit test)
Measurement of insulation resistance
Dielectric tests
Temperature rise
Tests on on-load tap-changer
Vacuum tests on tank and radiators

Routine tests of transformer include

Transformer winding resistance measurement
Measurement of voltage ratio and check of voltage vector relationship
Measurement of impedance voltage/short circuit impedance (principal tap) and load loss (Short circuit test)
Measurement of no load loss and current (Open circuit test)
Measurement of insulation resistance
Dielectric tests
Tests on on-load tap-changer
Oil pressure test on transformer to check against leakages past joints and gaskets.
That means Routine tests of transformer include all the type tests except temperature rise and vacuum tests. The oil pressure test on transformer to check against leakages past joints and gaskets is included.

Special Tests of transformer include

Dielectric Tests
Measurement of zero-sequence impedance of three-phase transformers
Short-Circuit Test
Measurement of acoustic noise level
Measurement of the harmonics of the no-load current
Measurement of the power taken by the fans and oil pumps
Tests on bought out components / accessories such as buchhloz relay, temperature indicators, pressure relief devices, oil preservation system etc.

**Transformer winding resistance measurement**

**Transformer winding resistance measurement** is carried out to calculate the I² R losses and to calculate winding temperature at the end of a temperature rise test. It is also done at site to ensure healthiness of a transformer that is to check loose connections, broken strands of conductor, high contact resistance in tap changers, high voltage leads and bushings etc.

**Procedure of Transformer winding resistance measurement**

For star connected winding, the resistance shall be measured between the line and neutral terminal.

For star connected auto-transformers the resistance of the HV side is measured between HV terminal and LV terminal, then between LV terminal and the neutral.

For delta connected windings, transformer winding resistance measurement shall be done between pairs of line terminals. As in delta connection the resistance of individual winding can not be measured separately, the resistance per winding shall be calculated as per the following formula:

\[
\text{Resistance per winding} = 1.5 \times \text{Measured value}
\]

The resistance is measured at ambient temperature and then converted to resistance at 75°C for all practical purposes of comparison with specified design values, previous results and diagnostics.

Winding Resistance at standard temperature of 75°C (R\text{75})
\[
R_{75} = R_t \frac{(235+75)}{(235+t)}
\]

\( R_t \) = Winding resistance at temperature \( t \).
\( t \) = Winding temperature
Generally transformer windings are immersed in insulation liquid and covered with paper insulation, hence it is impossible to measure the actual winding temperature in a de-energizing transformer at time of **transformer winding resistance measurement**. An approximation is developed to calculate temperature of winding at that condition, as follows

\[
\text{Temperature of winding} = \text{Average temperature of insulating oil.}
\]

(Average temperature of insulating oil should be taken 3 to 8 hours after de-energizing transformer and when the difference between top & bottom oil temperatures becomes less than 5°C)

The resistance can be measured by simple voltmeter ammeter method, Kelvin Bridge meter or automatic winding resistance measurement kit (ohm meter, preferably 25 Amps kit)

Caution for voltmeter ammeter method: Current shall not exceed 15% of the rated current of the winding. Large values may cause inaccuracy by heating the winding and thereby changing its temperature and resistance.

**NB: - Transformer winding resistance measurement shall be carried out at each tap.**

**Transformer Ratio Test**

The performance of a transformer largely depends upon perfection of specific turns or voltage ratio of transformer. So **transformer ratio test** is an essential type test of transformer. The voltage should be applied only in the high voltage winding in order to avoid unsafe voltage.

**Procedure of transformer ratio test**

1) First, the tap changer of transformer is kept in the lowest position and LV terminals are kept open.
2) Then apply 3-phase 415 V supply on HV terminals. Measure the voltages applied on each phase (Phase-Phase) on HV and LV terminals simultaneously.
3) After measuring the voltages at HV and LV terminals, the tap changer of transformer should be raised by one position and repeat test.
4) Repeat the same for each of the tap position separately.

The above **transformer ratio test** can also be performed by portable Transformer turns ratio (TTR) meter. They have an in built power supply, with the voltages commonly used being very low, such as 8-10 V and 50 Hz. The HV and LV windings of one phase of a transformer are connected to the instrument, and the internal bridge elements are varied to produce a null indication on the detector.
Out-of-tolerance transformer ratio test can be due to shorted turns, especially if there is an associated high excitation current.

Open turns in HV winding will indicate very low exciting current and no output voltage since open turns in HV winding causes no excitation current in the winding means no flux hence no induced voltage. But open turn in LV winding causes, low fluctuating LV voltage but normal excitation current in HV winding.

Hence open turns in LV winding will be indicated by normal levels of exciting current, but very low levels of unstable output voltage.

The transformer ratio test also detects high resistance connections in the lead circuitry or high contact resistance in tap changers by higher excitation current and a difficulty in balancing the bridge.

**Magnetic balance test of transformer**

Magnetic balance test of transformer is conducted only on three phase transformers to check the imbalance in the magnetic circuit.

**Procedure of Magnetic balance test of transformer**

1) First keep the tap changer of transformer in normal position.
2) Now disconnect the transformer neutral from ground.
3) Then apply single phase 230V AC supply across one of the HV winding terminals and neutral terminal.
4) Measure the voltage in two other HV terminals in respect of neutral terminal.
5) Repeat the test for each of the three phases.

In case of auto transformer, magnetic balance test of transformer should be repeated for IV winding also.

There are three limbs side by side in a core of transformer. One phase winding is wound in one limb. The voltage induced in different phases depends upon the respective position of the limb in the core. The voltage induced in different phases of transformer in respect to neutral terminals given in the table below.

<table>
<thead>
<tr>
<th>Voltage applied at left side phase</th>
<th>Left side phase</th>
<th>Central phase</th>
<th>Right side phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>230 V</td>
<td>AN</td>
<td>180 V</td>
<td>50 V</td>
</tr>
<tr>
<td>Voltage applied at central phase</td>
<td>115 V</td>
<td>230 V</td>
<td>115 V</td>
</tr>
<tr>
<td>Voltage applied at right side phase</td>
<td>50 V</td>
<td>180 V</td>
<td>230 V</td>
</tr>
</tbody>
</table>
**Magnetizing Current Test of Transformer**

**Magnetizing current test of transformer** is performed to:

- Locate defects in the magnetic core structure,
- Shifting of windings,
- Failure in turn to turn insulation
- Or problem in tap changers.

These conditions change the effective reluctance of the magnetic circuit, thus affecting the current required to establish flux in the core.

1) First of all keep the tap changer in the lowest position and open all HV & LV terminals.
2) Then apply three phase 415V supply on the line terminals for three phase transformers and single phase 230V supply on single phase transformers.
3) Measure the supply voltage and current in each phase.
4) Now repeat the magnetizing current test of transformer test with keeping tap changer in normal position.
5) And repeat the test with keeping the tap at highest position.

Generally there are two similar higher readings on two outer limb phases on transformer core and one lower reading on the centre limb phase, in case of three phase transformers. An agreement to within 30 % of the measured exciting current with the previous test is usually considered satisfactory. If the measured exciting current value is 50 times higher than the value measured during factory test, there is likelihood of a fault in the winding which needs further analysis.

Caution: This magnetizing current test of transformer is to be carried out before DC resistance measurement.

**Vector Group Test of Transformer**

In three phase transformer, it is essential to carry out a vector group test of transformer. Proper vector grouping in a transformer is an essential criteria for parallel operation of transformer.

Let’s have a YNd11 transformer.

**Procedure of vector group test of transformer**

1) Connect neutral point of star connected winding with earth.
2) Join 1U of HV and 2W of LV.
3) Apply 415V, three phase supply to HV terminals.
4) Measure voltages between terminals 2U – 1N, 2V – 1N, 2W – 1N, that means voltages between each LV terminal and HV neutral.
5) Also measure voltages between 2V – 1V, 2W – 1W and 2V – 1W.

For YNd11 transformer, we will find,
2U – 1N > 2V – 1N > 2W – 1N
2V – 1W > 2V – 1V or 2W – 1W

The vector group test of transformer for other group can also be done in similar way.

**Insulation Resistance Test or Megger Test of transformer**

**Insulation resistance test of transformer** is essential type test. This test is carried out to ensure the healthiness of over all insulation system of an electrical power transformer.

**Procedure of Insulation Resistance test of transformer**

1) First disconnect all the line and neutral terminals of the transformer.
2) Megger leads to be connected to LV and HV bushing studs to measure Insulation Resistance IR value in between the LV and HV windings.
3) Megger leads to be connected to HV bushing studs and transformer tank earth point to measure Insulation Resistance IR value in between the HV windings and earth.
4) Megger leads to be connected to LV bushing studs and transformer tank earth point to measure Insulation Resistance IR value in between the LV windings and earth.

NB : It is unnecessary to perform **insulation resistance test of transformer** per phase wise in three phase transformer. IR values are taken between the windings collectively as because all the windings on HV side are internally connected together to form either star or delta and also all the windings on LV side are internally connected together to form either star or delta.

Measurements are to be taken as follows:
For Auto Transformer: HV-IV to LV, HV-IV to E, LV to E
For Two Winding Transformer: HV to LV, HV to E, LV to E
Three Winding Transformer: HV to IV, HV to LV, IV to LV, HV to E, IV to E, LV to E

Oil temperature should be noted at the time of **insulation resistance test of transformer**. Since the IR value of transformer insulating oil may vary with temperature.
IR values to be recorded at intervals of 15 seconds, 1 minute and 10 minutes.

With the duration of application of voltage, IR value increases. The increase in IR is an indication of dryness of insulation.
Absorption Coefficient = 1 minute value/ 15 secs. value.
Polarization Index = 10 minutes value / 1 minute value