Electrical power transformer

By:

Ahmed Mohammed Alyousef & Hamed Sultan Alamry

al_yoosef_2009@hotmail.com h2med9@hotmail.com

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Supervisor:

Dr. Erik Loxbo

Examiner:

Dr. Sven Johansson
Abstract

The transformer is an electrical component in the distribution of power on the grid and other power systems. This thesis identifies various aspects of the transformer. The first part of the paper provides an overview of the general operation principle of the transformer. In addition, it highlights on various elements that enable the effective functioning of a power transformer. The thesis further establishes the theory of the transformer. In this case, it provides an overview of various factors that influence the performance of the transformer such as losses, for induced electromotive force (emf) equations and the concept of the step-up and step-down transformer.

The first chapter provides an overview of the principle, use and history of transformers. The second chapter describes, step up and step down transformers.

The third chapter is about the theoretical part of the transformer including EMF equation and the ratio of turns, voltage and current. Furthermore, we discuss the relationship between the magnetic flux density "B" and the magnetic field strength "H" and we describe how it behaves depending on core material. Moreover, we study the transformer losses including iron losses, copper losses, stray losses and dielectric losses. Thereafter, we discuss the efficiency of the transformer and its maximum efficiency. Furthermore, we provide an equivalent circuit of the transformer and after that the theory of a transformer with load.

The last chapter is about the operation of a transformer, we describe the normal operation and then we discuss the cooling system for transformers. Starting from the dry type transformers including two methods which are Air natural (AN) and Air forced (AF), followed by the oil immersed transformers which generally are used for larger sizes of transformers and we describe four cooling method ONAN, ONAF, OFAF and OFWF. Furthermore, we study the maintenance of transformers including the maintenance actions. Moreover, we describe transformer faults including external faults, internal faults and through faults. Last topic of this chapter is the transformer protection, we focus on one type of transformer which is oil immersed transformers. Therefore, we identify four type of faults that must be detected to avoid catastrophic failure; oil leakage, high temperature, high pressure and gas emission. The protection is performed using sensors for temperature, pressure and gas relay which are described.
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CHAPTER ONE: INTRODUCTION

1.1: principle of the transformer

A power transformer refers to a static device that transforms electrical energy from a particular circuit to another circuit without a direct electrical link using mutual induction between the windings. The transformer transforms power from a particular circuit to another with no frequency changes regardless of the voltage levels.

The transformer is a fundamental link in a power system that has made possible that power produced at low voltages (6600 to 22000 volts) can be increased up to high voltages for transmission over long distance and after that changed to low voltages for usage at appropriate load centers. With this apparatus in hands, it has changed to be usable to outfit the energy assets at distant places from the load centers and interface the same through long additional high voltage transmission lines working on high efficiencies.

The working principle of transformer relies on the Faraday's law of electromagnetic induction. Actually, the reason for the transformation action in an electrical transformer is the mutual induction between two or more windings. Generally, a transformer comprises of an iron core center and two or more arrangements of windings. Firstly, an alternating current (AC), is connected to one arrangement of windings, called the primary, which produces an alternating magnetic flux in the core of the transformer. This alternating flux will link to the secondary winding. Due to the phenomenon of mutual induction, an electromotive force (emf) will be induced in the secondary winding.

The number of turns in the secondary winding is responsible to identify whether the transformer is step up or step down. If the number of turns in the secondary are more than that in the primary, then the transformer is a step up transformer. However, if the number of turns in the secondary are less than that in the primary then the transformer is a step down transformer.
1.2: Use of power transformer

The most common and important device in an electric power system is a power transformer, while transformers are usually used for distribution the power. That a transformers used in many applications of power system such as widespread power distribution over a power grid, power distribution and voltage matching for power distribution to buildings, and providing low voltages for machine control.

The transformer is used to increase or decrease voltage and current reversely to suit a specific application. Step-u transformer normally utilized after the power plant, connecting between the power plant and the transmission lines, acting to increase the voltage very high and decrease the current simultaneously. Therefore, that will help to transport the power to long distance within transmission lines and avoiding the large losses.

Then, the power will go through transmission lines to a step-down transformer substation, which act to decrease the high voltage. After that, will continue to other transformer substation to a step-down the voltage more and step-up the current. Finally, after decreasing the voltage will transport to power distribution and voltage matching for power distribution to buildings.

1.3: History of the transformer

A transformer refers to a device converts electrical energy from one circuit then onto the next through inductively coupled circuits. A transformer is accustomed to bringing voltage up or down in an AC electrical circuit. A transformer can be utilized to change over AC power to DC power with help of a rectifiers. There are transformers everywhere in each house; they are inside the dark plastic case, which you connect to the socket to energize your mobile phone or different gadgets. These sorts are frequently called "divider warts." They can be substantial, as in national utility systems, or it can be little implanted inside hardware.

The property of induction was found in the 1830's yet it was not until 1886 that William Stanley, working for Westinghouse manufactured the first solid business transformer. His work was based on some simple plans by the Ganz Company in
Hungary (ZBD Transformer 1878), and Lucien Gaulard and John Dixon Gibbs in England. Nikola Tesla did not concoct the transformer as a few questionable sources have asserted. The Europeans specified above did the first work in the field. George Westinghouse, Albert Schmid, Oliver Shallenberger and Stanley made the transformer shoddy to create, and simple to modify for conclusive use.

The principal AC power system that utilized the current transformer was as a part of Great Barrington, Massachusetts in 1886. Prior types of the transformer were utilized as a part of Austro-Hungary 1878-1880s and 1882 ahead in England. Lucien Gaulard (Frenchman) utilized his AC system for the progressive Lanzo to Turin electrical piece in 1884 (Northern Italy). In 1891 genius, Mikhail Dobrovsky planned and exhibited his 3 stage transformers in the Electro-Technical Exposition at Frankfurt, Germany.
CHAPTER TWO: Types of transformers

There are several different kinds of transformers, they can be categorized in different ways according to their purpose, use and construction. We will deal with the transformer which is used in transmission and distribution power networks. There are two types of transformer used in transmission and distribution power system network. Namely, step up and step down transformer. Generally, they are used for stepping up and stepping down the voltage level in transmission and distribution of electrical power network.

A transformer comprises of a soft iron coil with two coils twisted around it, which are not joined to each other. These coils can either be twisted on isolated appendages of the iron center or be organized on top of one another. The coil that supplies the alternating voltage is known as the primary coil or primary winding. At the point when an alternating potential difference is supplied, the subsequent alternating current in the primary coil creates a changing attractive field around it. This changing field induces an alternating voltage in the secondary coil. The extent of the induce voltage coming about because of the impelled current in the secondary coil relies upon the number of turns in the secondary coil. Transformers are one of the most efficiency devices. If a transformer is 100% effective, then the power in the primary coil must be equivalent to the power in the secondary coil.

We know that:

\[ P = V \times I \]

If the transformer is 100% effective, then:

Power in primary coil = Power in secondary coil

\[ V_P \times I_P = V_S \times I_S \]

Where,

\( V_p \) = Voltage on the primary windings.

\( V_s \) = Voltage on the secondary windings

\( I_p \) = Current in the primary windings.

\( I_s \) = Current in the secondary windings.
2.1. Step-Down Transformer

A step-down transformer has fewer turns on the secondary coil than on the primary coil. The induced voltage in the secondary coil is less than the connected voltage over the primary coil or as it were; the voltage is stepped-down. If a transformer steps up the potential difference, then the current is stepped down by the same proportion. If the transformer steps down the voltage, then the same proportion steps up the current. The higher voltage beginning from the step-up transformer at the power plant is diminished by the utilization of a step-down transformer situated in a substation numerous miles away at the other side of the transmission line. The utilization of these substations of step-down transformer, successfully brings down the voltage and in the meantime raises the current at the other side of the line.

![Step-Down Transformer Diagram](image)

Figure 2.1: A Step-Down Transformer.

The relationship between the voltage and the number of turns in each winding is given by:

\[
\frac{V_p}{V_s} = \frac{N_p}{N_s}
\]

It can be written as:

\[
V_p \times N_s = V_s \times N_p
\]

To obtain the secondary voltage then it can be written as:

\[
V_s = \frac{V_p \times N_s}{N_p}
\]

The relationship between the current and the number of turns in each winding is given by:

\[
\frac{I_p}{I_s} = \frac{N_s}{N_p}
\]
It can be written as:

\[ I_p \times N_p = I_s \times N_s \]

To obtain the secondary current then it can be written as:

\[ I_s = \frac{I_p \times N_p}{N_s} \]

Where,

- \( V_p \) = potential difference (voltage) input on the primary coil
- \( V_s \) = potential difference (voltage) output on the secondary coil
- \( N_p \) = number of turns of wire on the primary coil
- \( N_s \) = number of turns of wire on the secondary coil
- \( I_p \) = Current in the primary coil
- \( I_s \) = Current in the secondary coil.

### 2.2. Step-Up Transformer

A step-up transformer is the direct inverse of a step-down transformer. There are more turns on the secondary winding than in the primary winding in the step-up transformer. In this manner, the voltage induced into the secondary transformer is higher than the one supplied over the primary winding. Due to the standard of conservation of power, the transformer changes from low voltage and high current to high voltage and low current. In other word, the voltage has been stepped up. The purpose to use a step up transformer is that, when a current flow in the transmission lines some energy is lost as heat. The higher current the more energy is lost. To avoid this heat losses, we make the current lower and therefore we step up the voltage. Step up transformers are used at the power station to produce the very high voltage needed to reduce the power losses on the transmission power network system. However, very high voltages are really dangerous for use in the home. Therefore, step down transformers are used at the distribution network to reduce the voltage to a safe level.
Figure 2.2: Step-Up transformer
CHAPTER THREE: THEORY OF TRANSFORMER

3.1: EMF Equation

Let,

\[ N_2 = \text{Number of turns in the secondary winding.} \]
\[ \Phi_m = \text{Maximum flux in the core (in Wb)} \]
\[ \Phi_m = (B_m \times A). \]
\[ f = \text{frequency of the AC supply (in Hz)} \]

As it is shown in the figure (3.1), the flux rises sinusoidally from zero to its maximum value \( \Phi_m \) in one quarter of the cycle \( 1/4f \).

The average rate of change of flux = \( \frac{\Phi_m}{4t} \) which is

\[ = 4f \Phi_m \text{ (Wb/s).} \]

Now, induced EMF per turn = rate of change of flux per turn.

Therefore, average EMF per turn = \( 4f \Phi_m \) (Volts).

Now, we know, Form factor = RMS value / average value.

Therefore, RMS value of EMF per turn = Form factor x average EMF per turn.

Since the flux \( \Phi_m \) varies sinusoidally, Form factor of a sine wave is 1.11

Now, RMS value of EMF per turn = \( 1.11 \times 4f \Phi_m. \)

RMS value of EMF per turn = \( 4.44 f \Phi_m. \)

Now, we can derive the whole RMS value of induced EMF in the primary winding \( (E_1) \) by multiplying the RMS value of EMF per turn by the number of turns in primary winding \( (N_1) \)

\[ E_1 = 4.44 f N_1 \Phi_m. \]
Similarly, RMS value of induced EMF in whole secondary winding \((E_2)\) can be derived as:

\[ E_2 = 4.44 \, f \, N_2 \, \Phi_m. \]

From the above equations \((E_1 = 4.44 \, f \, N_1 \, \Phi_m)\) and \((E_2 = 4.44 \, f \, N_2 \, \Phi_m)\). It is shown that, RMS value of induced EMF over the number of turns is the same for both primary and secondary windings.

\[ \frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44 \, f \, \Phi_m. \]

This is called the EMF equation of transformer.

Voltage transformation ratio \((K)\)

\[ \frac{E_2}{E_1} = \frac{N_2}{N_1} = K \text{, where } K = \text{constant.} \]

This constant \(K\) known as Voltage transformation ratio.

Notes:

- If \(N_2 > N_1\) i.e. \(K > 1\). The transformer is called step-up transformer.
- If \(N_2 < N_1\) i.e. \(K < 1\). The transformer is called step-down transformer.

### 3.2: Turns and Voltage Ratios

The transformation ratio of the transformer is known as mention in equation \((\frac{E_2}{E_1} = \frac{N_2}{N_1} = K)\).

\[ \frac{E_2}{E_1} = \frac{N_2}{N_1} = K \text{, where } K = \text{constant} \]

So, turns ratio is defined as:

\[ \text{Turns ratio} = \frac{N_1}{N_2} \]

While the voltage ratio is defined as:

\[ \text{Voltage ratio} = \frac{E_1}{E_2} \]
Turns ratio and voltage ratio of transformers are the same and known as a constant as mentioned before.

The relationship between the voltage and the number of turns in each winding can be expressed as:

$$E_p N_s = E_s N_p.$$  

Where:

- $E_p =$ Voltage applied to the primary.
- $N_s =$ Number of turns in secondary.
- $E_s =$ Voltage induced to the secondary.
- $N_p =$ Number of turns in primary.

From the equation ($E_p N_s = E_s N_p$), we can derive the voltage applied to the primary and secondary as:

For the secondary:

$$E_s = \frac{E_p N_s}{N_p}.$$  

For the primary:

$$E_p = \frac{E_s N_p}{N_s}.$$  

3.3: Magnetic Hysteresis:

Magnetic Hysteresis is the lag or delay of magnetic materials, due to the magnetization properties of the material which has been magnetized and then demagnetized.

We know that:

$$B = \frac{\phi}{A}.$$
Where:

B: the flux density with the unit Tesla (T).

\( \phi \): The amount of magnetic field within a given area.

A: the core area

Moreover, we know that the magnetic strength "H" of an electromagnet depends upon the number of turns of the coil, the current passing through the coil and the type of core material being used. Therefore, if we increase the current or the number of turns we can increase the magnetic field strength. The relationship between the flux density B and the magnetic field strength H can be defined by the magnetic permeability \( \mu \), as the ratio of flux density to the magnetic field as shown in the equation below:

\[
\mu = \frac{B}{H}.
\]

the relative permeability \( \mu_r \) is defined as the ratio of the absolute permeability \( \mu \) to the permeability of free space \( \mu_o \), this can be written as:

\[
\mu_r = \frac{\mu}{\mu_o}.
\]

Where:

\( \mu_o \); Is a constant \( 4\pi 10^{-7} \text{ H/m} \)

However, the relationship between the flux density B and the magnetic field strength H can be defined by the fact that the relative permeability \( \mu_r \) is not a constant but a function of the magnetic field intensity. This gave a magnetic flux density as:

\[
B = \mu H.
\]

Therefore, the magnetic flux density \( B \) in the material will be increased by a larger factor as a result of its relative permeability \( \mu_r \) for the material compared to the magnetic flux density \( B \) in vacuum, \( \mu_o H \) and for an air-cored coil or any non-magnetic medium core this relationship is given as:

\[
\frac{B}{H} = \mu_o.
\]

Eventually, for ferromagnetic materials the ratio of flux density to field strength \( B/H \) is not a constant but varies with flux density. However, for air cored coils or any non-
magnetic medium core such as woods or plastics, this ratio considered as a constant and known as $\mu_0$.

### 3.4: B-H curve:

A b-h curve is used to show the relationship between the magnetic flux density $B$ and the magnetic field strength $H$. This is also known as magnetization curve or magnetic hysteresis curve. Each type of material has its own curve, figure (3.2) shows an example of b-h curves for different materials.

![B-H Curves for Various Metals](image)

The set of magnetization curves above represents an example of the relationship between $B$ and $H$ for air, iron and steel cores. It shows that the flux density increases in proportion to the field strength until it approaches a certain value where it cannot increase anymore and becomes almost stable while the field strength continues to increase. The point on the graph where the flux density $B$ reaches its limit is called **Magnetic Saturation** and also known as **Saturation of the Core**. In our simple example figure (3.2), the saturation points of the steel curve start around 3000 ampere-turns per meter.

Saturation occurs because the random arrangement of the molecule structure within the core material changes as the tiny molecular magnets within the material become aligned. While the magnetic field strength $H$ increases these molecular magnets become more and more aligned until they reach perfect alignment producing maximum flux density $B$. However, any increase in the magnetic field strength $H$ because of an increase in the electrical current passing through the coil will have little or no effect. Furthermore, changing the direction of the magnetizing current through
the coil from a positive direction to a negative direction, as would be the case in an AC supply, a **Magnetic Hysteresis** loop of the ferromagnetic core will be produced.

**3.5: Magnetic Hysteresis Loop:**

![B-H behavior of a ferromagnetic core graphically](image)

Figure (3.3) shows the behavior of a ferromagnetic core graphically as the relationship between the magnetic flux $B$ and the magnetic field strength $H$ is non-linear. First of all, the core is demagnetized thus, both $B$ and $H$ will be at zero, point 0 on the magnetization curve. Then the magnetization current $i$ was increased in a positive direction to some value. Therefore, the magnetic field strength $H$ will increase with the current linearly and the flux density $B$ will increase until it reaches the saturation point as it shown by the curve from point 0 towards point a. Thereafter, the magnetizing current in the coil was reduced to zero so, the magnetic field circulating around the core reduces to zero too. However, the magnetic flux $B$ will not back to zero because of the residual magnetism present within the core, that’s shown on the curve from point a to point b. If we want to reduce the flux density to zero, we need to apply the current flowing through the coil in the negative direction. The magnetizing force which must be applied to make the residual flux density approach to zero is called a Coercive force. The coercive force causes the magnetic field rearranging the molecular magnets until the core becomes demagnetized again at point c. Moreover, increasing this negative current will cause the core to be magnetized again but in the opposite direction until the core reach its saturation point, this is shown on the curve from point c towards point d. Note that this point is
symmetrical to point b. If we reduce the magnetizing current again to zero, the residual magnetism present in the core will be equal to the previous value but in the negative direction at point e. Now if we change the magnetizing current passing through the coil to a positive direction again that will cause the magnetic flux B to be reduced to zero as it is show on the curve at point f. Increasing of the positive current further will cause the core to reach its saturation point at point a.

Finally, the B-H curve explained above is completed due to the magnetizing current flowing through the coil alternates between a positive and negative value. Therefore, it acts exactly like an alternating voltage applied to the ferromagnetic core. The importance of studying the magnetic hysteresis loop is that, to reduce the coercive force, because the coercive force which must be used to overcome the residual magnetism being dissipated as heat in the magnetic material. This heat is known as hysteresis loss. Moreover, the amount of this loss depends on the materials value of coercive force. Furthermore, hysteresis losses are always a problem in transformers, because the current is continuously changing direction so, the magnetic poles in the core will cause losses because of the continuously reverse direction. Therefore, it is very important to use very soft ferromagnetic materials such as iron or silicon steel in order to have a very narrow magnetic hysteresis loop, resulting in very small amounts of residual magnetism making them very perfect to use for transformers core since they can be easily magnetized and demagnetized. In other word, the smaller coercive force (more narrow hysteresis loop) we get the less hysteresis losses it has, resulting in an ideal transformer core. Figure (3.4) below shows different type of hysteresis loop for different materials.

![Hysteresis Loop Diagram](image)

Figure 3.4: hysteresis loop for different material.
3.6: Transformer Losses

Ideal transformer or the perfect transformer has no loss of energy. Therefore, the power on the primary is equal to the power on the secondary. However, practical transformer has a little loss. Thus, the power on the primary is not equivalent to the power on the secondary as long as the power loss on the secondary is considered.

Hence:

Power in primary coil = Power loss + Power in secondary coil

Nowadays, electrical power transformer designs typically between 95% to 98% efficiency. What is left of this percentage efficiency is a combination of different types of electric losses in the transformer. Iron losses, copper losses, stray losses and dielectric losses are the types of losses in the transformer as it shown in figure (3.5).

![Figure 3.5: Types of Losses in Transformer](image)

**3.6.1: Iron losses**

Iron losses is occurring in the core of the transformer so; it is known also as core losses. This kind of losses are caused by alternating flux in the core. Iron losses or Core losses consist of Eddy current loss and Hysteresis loss. Both of them depends on the magnetic properties of the material utilized to construct the core of the transformer and its design. Therefore, these losses are fixed and not depend upon the current load. So, it can be considered as a constant for all range of load.

- Core losses or Iron losses divided into the following:
  a) Hysteresis loss:
Hysteresis loss is because of inversion of magnetization in the transformer core. This loss relies on the volume and grade of the iron. Hysteresis losses is a power dissipated in the form of heat and it given on the following equation:

\[ W_h = K_\eta B_{max}^{1.6} f v \text{ (watts)}. \]

Where:

\( K_\eta = \) The proportionality constant which is depending upon the volume and the quality of the material of the core utilized in the transformer.

\( f = \) frequency in HZ.

\( B_{max} = \) The maximum value of the flux density in T.

\( v = \) The volume of the core in m3

To decrease this kind of losses some unique material is used such as silicon steel for the construction of the core of the transformer.

b) Eddy current loss:

An alternating current supply to the primary winding produces an alternating magnetizing flux in the core. Due to this flux, a voltage induced to the secondary winding causes a current flow to the load connected with it. Some of this alternating flux also links with the iron core of transformer which causes an induced emf. Due to this emf, a current will circulate locally in the iron core of transformer and not contribute in the output of the transformer and it will dissipate as heat. This kind of power loss is called eddy current loss of transformer. The equation of eddy current loss gives as following:

\[ P_e = K_e B_m^2 t^2 f^2 V \text{ (watts)}. \]

Where:

\( K_e = \) co-efficient of eddy current. Its value depends upon the volume, resistivity of core material and the thickness of laminations.

\( B_m = \) the maximum value of the flux density in (Wb/m²).

\( t = \) the thickness of lamination in meters.

\( f = \) the frequency of reversal of magnetic field in hertz

\( V = \) the volume of magnetic material in m³.
Making the core with thin laminations is the main factor to minimize the eddy current loss.

3.6.2: Copper loss:
Copper loss is because of Ohmic resistance of the windings of the transformer. The copper loss for the primary winding is \( I_1^2 R_1 \) and for secondary winding is \( I_2^2 R_2 \).
Where, \( I_1 \) is the current in Primary and \( I_2 \) is the current in the secondary winding, while \( R_1 \) and \( R_2 \) are the resistances of primary and secondary windings respectively. Moreover, \( I_1 \) and \( I_2 \) depend upon the load of the transformer. Therefore, copper losses are varying with the load of the transformer. The total copper loss in transformer can be defined as:

\[
P_c = I_1^2 R_1 + I_2^2 R_2.
\]

Since, these losses are varying according to the current load, it's also known as variables loss.

3.6.3: Stray loss:
Stray losses occur because of the presence of the leakage fields. These kind of losses are small compared to iron and copper loss. Therefore, they can often be neglected.

3.6.4: Dielectric loss:
Dielectric loss occurs in the transformer oil and other solid insulating materials in the transformer.

All these different types of losses in transformer are dissipated in the form of heat in the winding, core, insulating oil and wall of the transformer. However, the main losses occur in the transformer are core loss and copper loss. While stray and dielectric loss are very small. If these losses are decreased, it results in high efficient transformer.
3.7: Transformer Efficiency

Transformers are among the most efficient electrical gadgets. An ideal transformer efficiency is equal to the output power partitioned by the input power. Efficiency = output/input. A large portion of the transformers has full load productivity between 95% and 98.5%. As a transformer being profoundly effective, output and input are having almost the same worth, and thus it is impractical to quantify the productivity of transformer by utilizing output/input. Therefore, the accurate method to define the efficiency of transformer is by,

\[ \text{efficiency} = \frac{\text{output} - \text{losses}}{\text{input}} = 1 - \frac{\text{losses}}{\text{input}}. \]

3.7.1: Maximum Efficiency

Let,

- Copper loss = \( I_1^2 R_1 \)
- Iron loss = \( W_i \)

\[ \text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2 R_1 + W_i}{V_1 I_1 \cos \Phi_1} \]

\[ \eta = 1 - \frac{I_1 R_1}{V_1 \cos \Phi_1} - \frac{W_i}{V_1 I_1 \cos \Phi_1} \]

differentiating above equation with respect to \( I_1 \)

\[ \frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1 \cos \Phi_1} + \frac{W_i}{V_1 I_1^2 \cos \Phi_1} \]

\[ \eta \text{ will be maximum at } \frac{d\eta}{dI_1} = 0 \]

Hence, \( \eta \) will be maximum at

\[ \frac{R_1}{V_1 \cos \Phi_1} = \frac{W_i}{V_1 I_1^2 \cos \Phi_1} \]

\[ \frac{I_1^2 R_1}{V_1 I_1^2 \cos \Phi_1} = \frac{W_i}{V_1 I_1^2 \cos \Phi_1} \]

\[ I_1^2 R_1 = W_i \]

Hence, efficiency of a transformer will be maximum when copper loss and iron losses are equal.

That is Copper loss = Iron loss.

3.8: Equivalent circuit

The equivalent circuit of a transformer is a simple array of electrical components that is electrically equivalent to a complex circuit. The equivalent circuit is used to simplify circuit analysis and helpful in predetermining the behavior of the transformer under various conditions of operation from the known equivalent circuit
parameters. A practical transformers have a resistances and reactance. Whereas, an elements of equivalent circuit are the leakage reactance, the load losses, the core losses and the magnetizing reactance. Where the leakage flux is present at both primary and secondary sides.

This leakage gives rise to leakage reactances at both sides, which $X_p$ stand for the leakage reactance of primary side and $X_n$ stand for the leakage reactance secondary side respectively. $R_p$ and $R_s$ are stand for a primary and secondary resistances of a winding in both side respectively. These resistances disease voltage drop and that denotes as, $I_p R_p$ and $I_n R_s$ and also copper loss $I_p^2 R_p$ and $I_n^2 R_s$ in both side as well. In the core, some of magnetizing current is needed, because of the permeability of the core cannot be infinite. Moreover, mutual flux is also reason of core loss in iron parts of the transformer.

By considering the voltage drop across the primary and secondary winding, the practical transformer is assumed to be equivalent to an ideal transformer along with the additional impedances inserted between the supply and the primary winding and between the secondary winding and the load of the equivalent circuit as it is shown in figure 3.6:

![Figure 3.6: Equivalent Circuit of Transformer.](image)

The current which called $I_0$ in the equivalent circuit above is divided into, pure inductance $X_0$ (taking magnetizing components $I_0$) and non-induction resistance $R_0$ (taking working segment $I_w$) which are connected into parallel across the primary and with no load. The estimation of $E_p$ is obtained by subtracting $I_p Z_p$ from $V_p$. The
estimation of \( R_0 \) and \( X_0 \) can be figured as:
\[
R_0 = \frac{E_p}{I_w} \quad \text{and} \quad X_0 = \frac{E_p}{I_\mu}.
\]

From the voltage transformation ratio;
\[
\frac{E_p}{E_s} = \frac{N_p}{N_s} = K.
\]

However, impedances in primary side and secondary side are impossible to add them
\((R_p + R_s \text{ and } X_p + X_s)\) and make calculations simple. Wherefore, it can be possible if
we replace current, voltage and impedance either to primary side or to the secondary
side. In that case, we would have to work first with equivalent circuit of transformer
with secondary parameters referred to the primary. and that will simplify the
calculation more than the above circuit (3.6).

\( Z_s \) can be referred to primary as \( Z_s' \).

where,
\[
Z_s' = \left(\frac{N_p}{N_s}\right)^2 Z_s = K^2 Z_s.
\]

\( K = \frac{N_p}{N_s} \).

that is,
\[
R_s' + jX_s' = K^2 (R_s + jX_s)
\]
equating real and imaginary parts,
\( RS' = K^2 R_s \) and \( X_s' = K^2 X_s \).

And \( V_s' = KV_s \).

The figure (3.7) below shows the equivalent circuit of transformer with secondary
parameters referred to the primary.
Now, since $I_o$ is very small compared to $I_1$, which is less than 5% of full load primary current. Therefore, the exciting current would affect insignificantly to the parallel values of winding resistance $R_o$ and leakage reactance $X_0$. That mean $V_p$ and $E_p$ can be assumed to be equal. Hence, the equivalent circuit of transformer can be simplified more, by neglecting the parallel which consists of the resistance $R_o$ and reactance $X_0$ without introducing any appreciable error in the equivalent circuit of the transformer.

Now the equivalent circuit after neglecting $R_o$ and $X_0$ are shown in the figure (3.8):

![Figure 3.8: the equivalent circuit after neglecting $R_o$ and $X_0$](image)

Now, let's simplify the impedances by summing $R_p$ and $R_s$' together, also let's sum $X_p$ with $X_s$.

Hence, $R_{eq} + R_s$

$$R_p + R_s' = R_{eq} \text{ and } X_p + X_s' = X_{eq}$$

Then the final approximate equivalent circuit of transformer becomes as shown in the figure (3.9) below:

![Figure 3.9: Approximate Equivalent Circuit of Transformer referred to primary.](image)
3.9: Theory of Transformer on Load

A transformer on load implies that a load is associated with the secondary terminals. Consider, transformer having core loss however no copper loss and spillage reactance. At whatever point load is associated with the secondary winding, load current will begin to move through the load and in addition in the secondary winding. This load current singularly relies on the qualities of the load and 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 coursing through the secondary, a self-mmf in secondary winding will be delivered. Here it is $N_2I_2$, where, $N_2$ is the quantity of turns of the secondary twisting of transformer.

The mmf or magneto thought process power in the secondary winding produces flux $\phi_2$. This $\phi_2$ will contradict the principle magnetizing flux, in the blink of an eye weakens the fundamental flux, and tries to lessen primary self-incited emf $E_1$. In the event that $E_1$ tumbles down beneath the primary source voltage $V_1$, there will be an additional current spilling out of source to primary winding. This additional primary current $I_2'$ creates additional flux $\phi'$ in the core that will neutralize the secondary counter flux $\phi_2$. Thus, the primary magnetizing flux of core, $\Phi$ stays unaltered regardless of load.

The aggregate current the transformer draws from source is isolated into two components, initial one is used for magnetizing the core and repaying the core loss that is $I_0$. It is no-load segment of the primary current. Second, one is used for remunerating the counter flux of resistance the secondary winding. The aggregate no load primary current $I_1$ of a transformer having no winding resistance and spillage voltage can be indicated as:

$$I_1 = I_0 + I'_2.$$
CHAPTER FOUR: OPERATION OF TRANSFORMERS

4.1. Operation of Transformers

The transformer operates based on the concept that energy can be effectively exchanged by magnetic induction starting with one winding then onto the next alternating to wind by a varying magnetic field created current. An electrical voltage is induced when there is a relative movement between a wire and a magnetic field. Exchanging current, (AC) gives the movement required by altering course, which makes a crumpling and growing magnetic field. The two windings are connected together with a magnetic circuit that must be regular to both windings. The connection associating the two windings in the magnetic circuit is the iron core on which both windings are wound. Iron is a greatly decent conductor for magnetic fields. The core is not a solid bar of steel, yet is developed of numerous layers of slight steel called laminations. One of the windings is assigned as the primary and the other winding as the secondary. Since the primary and secondary are twisted on the same iron core, when the primary winding is energized by an AC source, an exchanging magnetic field called flux is set up in the transformer core. The flux made by the connected voltage on the primary winding induces a voltage on the secondary winding. The primary winding acquires the energy, which is known as the input. The secondary winding releases the energy and is known as the output.

![Figure 4.1](image_url)

The primary and secondary windings comprise of aluminum or copper channels twisted in curls around an iron core and the quantity of turns in every loop will decide the voltage transformation of the transformer. Every turn of wire in the primary winding has an equivalent offer of the primary voltage. The same is instigated in every turn of the secondary. In this manner, any distinction in the quantity of turns in the secondary when contrasted with the primary will deliver a
voltage change. In many transformers, the high voltage winding is twisted specifically over the low voltage winding to make effective coupling of the two windings. The voltage transformation is an element of the turns proportion. It might be alluring to change the proportion to get evaluated yield voltage when the approaching voltage is somewhat not the same as the normal voltage.

4.2. Cooling System
Since an ideal transformer is not achieved yet so, practical transformers have different types of losses such as copper loss, hysteresis loss and eddy current loss. These losses in the transformers are approximately 1% of its full load rating. Most of these losses are converted into heat. Increasing this heat will rise the temperature of the transformer continually which may cause damages in paper insulation and liquid insulation medium of the transformer. Therefore, it is essential to use an external cooling system to control the temperature within certain limits to ensure long life of the transformer.

4.2.1. Transformer Cooling Methods
There are different cooling methods used in electrical power transformer depending upon their size and ratings. The bigger transformer size we have the more sophisticated cooling method it needs.

   Transformer cooling methods can be divided in two types:

1) **Dry type transformers.**

   This method also can be divided in two types:

   a) **Air natural (AN)**

       Air natural or self-air cooled transformer is generally used for small ratings transformers up to 3 MVA. Basically, this method uses the natural air flow surrounding the transformer as cooling medium. Thus, heat will dissipate in air automatically.

   b) **Air forced (AF)**

       Air natural method is inadequate to use it for transformers rated higher than 3MVA. Therefore, fans or blowers are required to force the air towards the core and windings so, hot air is gained cooled due to the outside natural conventional air.
However, the air forced should be filtered in order to prevent the accumulation of dust particles in ventilation ducts. This method is useful for transformers rated up to 15MVA. Figure (4.2) shows an example of forced air cooled transformer.

Figure 4.2: forced air cooled transformer.

2) Oil immersed transformer

This is the most common cooling method for electrical power transformers. Generally, the transformer core and windings are immersed in the oil which has a good electrical insulating property and high thermal conductivity.

This method can be divided into four types regarding to their size and ratings.

a) Oil Natural Air Natural (ONAN).

This method of transformer cooling is widely used for oil immersed transformers rated up to 30MVA. The heat which is generated in the winding and core will transferred to the oil in the tank. Furthermore, we know that hot oil flows upward and the cold oil comes down according to the principle of convection. Therefore, the heated oil flows in the upward direction and then will goes via the tubes or radiators. While these tubes or radiators filled with cold oil so, the hot oil which comes from the upper portion of the radiators will push the cold oil down to the oil tank, and the heated oil will dissipate in the radiators due to the natural air flow around the transformer. In this manner, the oil in the transformer tank will keeps circulating
because of natural convection and it will dissipate the heat in atmosphere due to natural conduction. Figure (4.3) shows an example of oil natural air natural.

![Diagram of Oil Natural Air Natural Cooling of Transformer](image)

**Figure 4.3: Oil Natural Air Natural Cooling of Transformer**

b) **Oil Natural Air Forced (ONAF).**

Oil natural air natural is not enough to cool the transformer rated higher than 30 MVA. Thus, the dissipating surface can be improved by applying forced air such as fans. Forced air gives faster heat dissipation than natural air. In this manner, fans are mounted near to the radiator surface and it can be provided with an automatic speed arrangement, to control the fans by turn it on or to give the fans higher speed to keep the temperature at permissible limit. Generally, oil natural air forced method is useful for transformers rated up to 60MVA. Figure (4.4) shows an example of oil natural air forced cooling of transformer.
For transformers rated higher than 60MVA, oil natural air forced is not adequate to dissipate the heat properly. Thus, oil circulation needs to be improved in somehow. Therefore, the oil circulation can be forced through the radiators with the help of a pump, then compressed air is forced to flow on the radiators with the help of fans. Furthermore, the radiators or heat exchangers can be designed to be mounted separately from the transformer tank and connected via pipes at top and bottom of the transformer tank. Generally, oil forced air forced cooling method is provided for high rating transformers at substations or power stations. Figure (4.5) shows an example of oil forced air forced cooling method.
d) Oil Forced Water Forced (OFWF).

We know that the ambient temperature of the atmosphere air is much higher than the water in same weather condition. Thus, water can be used for better heat exchanger medium than air. Furthermore, oil forced water forced cooling system designed to be separately from the transformer tank, the hot oil forced to flow via the top pipe with the help of pump to the heat exchanger, while the cold water forced to flow in the heat exchanger with help of pump too. Note that, oil not mixed with cold water in the heat exchanger. Moreover, the hot oil dissipates the heat in the cold water which is taken away to cool again in separate coolers. While the cooled oil which comes out from the heat exchanger are back again to the transformer through the bottom pipe. Generally, oil forced water forced cooling system used in very large transformers rated higher than 500MVA. An example of OFWF shown in figure (4.6).

Figure 4.6: Oil Forced Water Forced Cooling of Transformer

4.3. Maintenance of Transformer

The unwavering quality and execution of a transformer is significant to power dissemination. Any breakdown of such gear involves loss of income for both suppliers and in addition customers. Accordingly, it is of highest significance to keep them operational all through their presence. Support is the best way to keep them fit for obligation. Minor debasement in transformers and circuit breakers ought not to be disregarded because in the end it turns into the powerless point in the hardware. Recognizing these shortcomings ahead of time causes from various perspectives to
minimize upkeep cost, forestall unexpected blackouts and give smooth force dissemination on the system. Nonstop checking of this hardware should be completed forever with a specific end goal to distinguish any corruption and disappointments utilizing legitimate instruments taking into account producers information. Utilizing the information gathered, the condition appraisal of every gadget can be developing. While the working standards of transformers have continued as before for about a century, the difficulties of keeping up and testing transformers have developed alongside transformer outline and development. Present day transformers are intended to closer resistances than at any other time. Appropriate testing is fundamental for assessing the state of a transformer.

4.3.1. Maintenance Actions

1. The oil level in oil top under silica gel breather must checked in one-month interim. In the event that it is discovered the transformer, oil inside the glass comes below the predefined level, oil to be beat up according to indicated level.

2. Breathing openings in silica gel breather ought to additionally be checked month to month and legitimately clean if require, for appropriate breathing activity.

3. In the event that the transformer has oil, filled bushing the oil level of transformer oil inside the bushing must be independently checked in the oil gage appended to those bushing. This activity additionally to be done month-to-month premise.

4.4. Faults in Transformer

4.4.1. External faults

As external faults in power transformer we have external Short-Circuit of Power Transformer. This may occur in two or three phases of electrical power system. The level of fault current is always high enough. It depends upon the impedance of the circuit up to the fault point and upon the voltage which has been short - circuited. 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. During first cycle of symmetrical fault current the maximum mechanical stresses can occur.

In high voltage there are two major types of high voltage disturbance in power transformers, which are a transient surge voltage and power frequency over voltage.
1. Transient Surge Voltage:

It is basically a wave with high frequency and steep wave form. In electrical power system network this wave travels and when it reaches transformer it breaks the insulation between turns adjacent to line terminal. This breakdown of insulation may cause short circuit between turns. A major causes of transient surge current are switching operations in electrical systems, lightning Impulse and arcing ground.
2. **Power Frequency Over Voltage:**

We know that a sudden disconnection of large load causes a sudden increase in amplitude of voltage while frequency remains same. This over voltage can cause an increase in stress on insulation of transformer. We are aware that Voltage is directly proportional to flux i.e. an increase in voltage causes an increase in flux. Ultimately increase in flux increases the magnetizing current and copper losses. This flux is transformed to different part of transformer like core bolts and other steel structure parts. Core bolts which carry a small flux they may be subjected a large flux and under such condition they may heat up rapidly and destroy their own insulation along with winding insulation.

4.4.2. **Internal Faults**

Internal flaws are the deficiencies, which happen inward to the transformer that might genuinely harm the protection of the transformer, and causes separate in transformer. Therefore, the transformer ought to be instantly shielded from these flaws. These issues are separated as electrical and mechanical shortcomings.

**Electrical deficiencies:** Phase-to-Phase shortcoming, Phase to ground, inter turn blames additional will go under electrical inner issues. On account of winding protection, disappointment, which often makes, short circuits between short out between stage to stage or stage to ground results in high current flow. This high current flow might separate the winding or even it might likewise harm the core completely.

**Mechanical Faults:** Transformer cooling media flaws, Transformer changing issues are considered as mechanical issues. The cooling medium disappointment results in high temperatures in transformer that influences the protection and packaging. In long run, this may come about weakening of segment or even it might likewise make fire in the transformer. In transformer, tap changing instrument there will be high current flow in the taping, if any flaw in this component might bring about blazing at tap changers.

4.4.3. **Through Faults**

Through faults happen outside the transformer zone and cleared by the downstream components. In any case, they do not clear the shortcoming; it might bring about
serious over loading on transformer, which brings about extensive current flow through the transformer. On the off chance, that the deficiency is at secondary side then a substantial current flow will bring about secondary and it reflects high current flow in relating primary winding. These shortcomings are not genuine yet these may fall apart the protection of the transformer and might make long time flaw.

4.5. Transformer Protection

Electrical power transformers are one of the main components in power system. Starting from the very high power transformer rated higher than 500MVA which is usually located at the power stations, or the medium size of transformers which can be founded at the distribution station. Faults in all sizes of transformers are common and costly. It is so dangerous if it's not protected properly. The whole transformer might be damaged and may leads the power station to be shut down in case of high power transformers used at power stations. However, distribution transformers may leave thousands of houses without electricity. Therefore, electrical power transformers must be protected in very high level to avoid any unwanted consequences. Furthermore, transformer protection reduces the risk of catastrophic failure to simplify eventual repair and to minimize the time of disconnection for faults within the transformer. An extended operation of the transformer under abnormal condition will diminish the life of the transformer. This means we should provide adequate protection for quicker isolation of the transformer under such conditions.

However, there are many different types of transformers depending upon their size, use and location on the power system, each of them may have different type of protection too. Therefore, it's quite difficult to cover all the transformers protections. So, we will discuss further one type of high power transformer that is oil immersed transformers. There are three common protection devices used in oil immersed transformer Buchholz gas relay, pressure relay and DMCR relay.
1) Buchholz (gas) relay.

The Buchholz relay is an electromechanical faults detector used in oil immersed transformers. The Buchholz gas relay is placed in the connecting piping between the transformer tank and the oil conservator as it shown in figure (4.7). Often the Buchholz gas relay is installed in a bypass pipe to make it possible to take it out of service. For reliable operation, the conservator pipe must be slant slightly.

The faults in oil immersed transformers can be divided in two type of faults, namely incipient faults and major faults.

**The incipient faults are like:**

- Current through defective supporting and insulating structures
- Defective windings
- Core fault

**The major faults are like:**

- Short between turn and windings
- Short between phase to phase.
- Open circuit.

The Buchholz gas relay provides two functions, an alarm signal when an incipient faults detected in the transformer. Also it initiating disconnection of the transformer when a major fault has been detected in the transformer.
**How the Buchholz gas relay identify the faults!**

The Buchholz gas relay can identify the transformer faults regarding to the gas in the oil. When an incipient faults happen in the transformer, it will heat up the oil slowly and produces ionize gases. These gases will go up towards the conservator, accumulates in the Buchholz relay until its exceed permissible limit then it will give an alarm signal. However, a major fault is identified by the Buchholz gas relay by the fact that, when a major faults happen in a transformer it will produce rapidly a large volume of gases. These large volume of gases causes a steep buildup of pressure and displace oil. This rapid oil flow from the transformer tank towards the conservator. Thus, the Buchholz gas relay will sense this rapid flow in somehow and will disconnect the transformer.

**Function of the Buchholz relay:**

Figure (4.8) below shows an example of the Buchholz (gas)relay which consist of a double float, each one carries a mercury switch.

![Figure 4.8: Function of the Buchholz relay:](image)

During the normal operation, the Buchholz relay is completely filled with oil and the tow floats at the top of their position due to buoyancy and both of the mercury switches are open as it shown in the blue color in the figure (4.8). However, when an incipient faults occurs in the transformer, the gas in the oil moves upwards and will accumulates in the Buchholz relay and effecting the oil level. This will cause the upper float to move and close the circuit and an alarm signal is tripped, while the lower float will not have effected and the gas will flow to the conservator.
Figure (4.9) shows the situation when a major fault occurs in the transformer, the oil flow will reach the damper in the relay, if the damper has been moves in flow direction, the lower float will move and close the circuit and will cause the transformer to be disconnected. Furthermore, the Buchholz relay can detect the very low oil level too in case of leakage. If the oil level falls, the upper float will move down. Thus, an alarm circuit is tripped. If the oil level decreasing continually until the conservator, piping and the Buchholz relay become empties.

Thus, the lower float will move too and actuates a switch contact so, the transformer is disconnected. Figure (4.10) below shows the example of oil loss due to leakage.

2) Pressure Relay.

A pressure relay is device used to protect an oil tank of tap changer of the transformer or the oil tank of transformer, when happen some faults which cause a sudden pressure in the oil tank more than normal. In the figure (4.11) below show a pressure relay with its component.
The pressure relay devices operate to detected a sudden excessive pressure within the transformer tank and exerts pressure directly on the spring, then the pressure force will move piston to operate the switching contacts. Within a switching unit, micro switch and pressurized nitrogen gas too, into switch unit which have closed tightly.

That pressure into oil tank of the power transformer is really dangers. It's can cause miserably failure such rupture the tank, also destroy other equipment and fire. Therefore, the pressure relay is very important to protect equipment and laborers, and keep the area safe.

The easiest way to relief the pressure by using pressure relief device with frangible disk as it shown in figure (4.12), which is the widely used. That surge of oil inside the tank caused by a heavy internal fault bursts the disk and allows the oil to discharge the pressure rapidly. Such that, will help to relieve, limit the pressure rise and prevent explosive rupture of the tank and outbreak the fire.
The pressure relief device is can be connect with "contact units" to send a signal to the circuit breakers and shutdown the transformer.

![Figure 4.13: Pressure relief device.](image)

However, the oil remaining in the tank will leave uncovered and exposed to the atmosphere after breaking a frangible disk. That is defect to the operate of the frangible disk after discharge the oil; so, that avoided by use the pressure relief valve which opens to allow the discharge of oil if the pressure exceeds the pre-adjusted limit. When the pressure been abnormal, the "spring controlled" of valve will operating into a few milliseconds and provide fast tripping when suitable contacts are fitted, then the valve will be closes automatically as the internal pressure falls below a critical level.

Thus, the overpressure can be limited to a magnitude harmless to the transformer by provide a pressure relief valve.

3) **DMCR protection relay.**

![Figure 4.14: DMCR protection relay.](image)
The detection, measurement and control relay "DMCR" is one common protection device used in oil immersed transformers. This device continuously monitors and complete control the oil parameters i.e. pressure, temperature, oil level and gas detection. Moreover, this device has a tow features, the DMCR casing is a transparent reservoir which enables 360° visibility of the dielectric fluid, and the magnet which trips the dielectric fluid contact is ring shaped and shields the reed switch from the influence of any external magnetic field up to 25mT.

3.1) The DMCR installation and components.

Generally, the DMCR is placed directly on the top of the transformer thank. The DMCR consist of a tow red float to monitor and detect the oil level and the gas emission on the transformer tank, one is small and located on the upper while the main (big) float is located on the lower part of the DMCR as it shown on the figure-(4.14). Moreover, it has one thermometer and two adjustable thermostat switches for monitoring the oil temperature for two different level of temperature. In addition, it has one adjustable pressure switches for monitoring the pressure on the transformer tank.

3.2) The faults and detections.

Firstly, the DMCR relay is fully filled with oil and connected to the top oil of the transformer tank. So, the tow floats are at the top position as it shown in the figure (4.15). This is the normal condition of the DMCR relay.

Figure 4.15: The normal condition of the DMCR relay.
If any faults happen in the transformer it will effects the oil in the transformer tank such as in case of a short circuit in the transformer or overload, it will cause the oil temperature to be increased and it will cause a heavy gas in the transformer tank which will accumulate in the DMCR too. The DMCR relay is continuously monitoring the oil parameters in the transformer tank such as oil level, temperature, gas and pressure. Any change of these parameters will detected by the DMCR relay as a fault. These faults and how they will be detected by the relay can be divided into three different cases as follows:

i. Oil level control and gas detection.

Oil level can be drop due to leak in the transformer tank, also oil level in the relay can be drop due to the presence of gasses in the transformer tank. Often, gasses emission happens due to the overload or short circuit in the transformer which will causes the gasses to moves upwards in the oil and accumulate in the DMCR relay. These gases initially cause the oil level to be drop in the upper part of the relay thus the secondary float will be at the bottom and it switch contact and generates an alarm circuit, this action is happening in case of leakage in the transformer tank as well. Increasing this leakage or gasses leads the main float to be at the bottom position too. In this case, the main float will trigger an electrical circuit which will de-energized the transformer unit.

ii. Pressure control.

There is several reason responsible for high pressure in the transformer tank such as overload, short circuit and overheating. However, the DMCR relay is able to detect an excess pressure limit in the transformer tank due to the pressure captor unit, it has one adjustable pressure switch with changeover contact. The tripping overpressure threshold of the pressure switch can be set within 100mbar to 500mbar rang. In case of high pressure in the transformer tank, the DMCR relay is able to detect this pressure due to a soft membrane which deforms under pressure and actuate a changeover contact which de-energized the transformer unit. Figure (4.16) shows the pressure captor unit.
Temperature control.

This is one of the most important zones that must be monitored and protected in all the transformer life. Often, all kinds of faults which can happen in the transformer will result in rising up the oil temperature such as overload, short circuit and improper cooling equipment. Therefore, the DMCR relay is used to detect the high temperature oil at two different levels of temperature. So, it has one thermometer and two adjustable thermostats which can be set within 30° C to 120° C range. The primary thermostat is to activate a temperature alarm while the secondary thermostat is to trip a de-energize circuit. So, the transformer is disconnected. Figure (4.17) shows the adjustable primary and secondary thermostats.

However, the thermostats are feature a changeover contact activated by a membrane connected by a capillary tube to a temperature probe placed deep inside the
central brass tube which is immersed in the transformer tank. The probe and capillary tube are filled in with a liquid which expands proportion to the oil temperature surrounding the probe.
CHAPTER FIVE: CONCLUSION

Electrical power transformer is one of the most important components of the power system. It used to step up and down the voltage for a transmission and distribution system. Moreover, it features a very high efficiency up to 99% on load. However, this remaining percentage which is 1% is a combination of different kinds of losses such as core loss and copper loss, reducing these losses will lead us to the ideal transformer.

In other hand, electrical power transformers are so dangerous, not only for the engineers who works with it but also it is dangerous for human, animals and the environment. Therefore, it is very important to study the transformer faults in order to find an adequate protection.
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