Sensor and Power Transformers

Prepared by

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Second Year

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Acknowledgments

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توصيف مقرر دراسى

1- بيانات المقرر		
الرمز الكودى :	اسم المقرر : الحساسات ومحولات الطاقة **Sensors and Power Transformers**	الفرقة /المستوى :
التخصص :	عدد الوحدات الدراسية : 2 نظرى 2 عملى	

2- هدف المقرر:	This course aims to: This course will equip the students with knowledge and skills related to the construction, operation principles, and cooling methods of single-phase and three-phase power transformers and the principles, functions, and applications of instrument transformers as electromagnetic induction based sensors.
3- المستهدف من تدريس المقرر :	
ا. المعلومات والمفاهيم :	**By the end of this course, the students should be able to:** a1- Identify the magnetic properties of various materials. a2- Explain the basic theories of electromagnetism, and electromagnetic induction. a3- Describe the main constructional features of single-phase and three-phase power transformers. a4- Explain the operation principles of power transformers. a5- Identify the cooling methods of power transformers. a6- Describe the basic principles of instrument transformers. a7- State Explain the applications of various types of transformers.
ب- المهارات الذهنية :	b1- Discuss the required properties of materials used in the construction of various types of transformers. b2- Analyze the applications of various types of transformers. b3- Synthase the internal structures, and cooling methods of various types of power transformers.
ج- المهارات المهنية الخاصة بالمقرر:	c1- Estimate the basic operational characteristics and losses of instrument and power transformers. c2- Perform the basic modeling and calculations of various types of sensor and power transformers. c3- Specify potential and current transformers as sensors. c4- Specify suitable cooling method for a power transformer.
د- المهارات العامة :	By the end of this course, the students should be able to: d1- Write technical report. d2- Present scientific work. d3- Work in a team.

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4- محتوى المقرر:

Week	Topic
1	Magnetic properties of materials
2	Basics of electromagnetism
3	asics of electromagnetic induction
4	onstruction of single-phase power transformers
5-6	peration principles of single-phase power transformers
7	lid-term exam
8	lulti-winding single-phase power transformers
9	ooling methods
10	hree-phase power transformers
11	rinciples and applications of current sensing transformers
12	rinciples and applications of voltage sensing transformers
13	isit of a power distribution substation
14	Discussions
15	- (Final exam)

5- أساليب التعليم والتعلم	4.1 - Lectures 4.2 – Assignments 4.3 - Site visit
6- أساليب التعليم والتعلم للطلاب ذوى القدرات المحدودة	Special care will be given for applicable and acceptable cases.
7- تقويم الطلاب :	
أ- الأساليب المستخدمة	**1.** Assignments **2.** Quizzes **3.** Midterm exam **4.** Site visit **5.** Final exam
ب- التوقيت	**1.** Assignments (1st to 13th week) **2.** Quiz (5rd,week) **3.** Midterm exam (7th week) **4.** Site visit and/or Project (13th week) **5.** Final exam (15th week)
ج- توزيع الدرجات	Quiz : 3 mark Midterm: 5 marks Attendance 2 marks Clinical: 10 marks Final written exam 80 marks. Total percentage 100 mark

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8- قائمة الكتب الدراسية والمراجع :	
أ- مذكرات	To be delivered to the students as presentations.

ب- كتب ملزمة	The course textbook.
ج- كتب مقترحة	[1] Harlow JH. Electric power transformer engineering. CRC press; 2012. [2] Bakshi KB. Electrical Measurements & Measuring Instruments. Technical Publications; 2007. [3] John J, Winders J. Power Transformers Principles and Applications. New York. 2002:27-153. **[4]** Gönen T. Electric power distribution system engineering. New York: McGraw-Hill; 1986.
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Contents

حقوق النشر والتأليف لوزارة الصحة والسكان ويحذر بيعه

Course Description

This course presents electromagnetic transformers for use in power and sensing applications. It is prepared for high-level technical, non-engineering students working in medical facilities, and industrial systems. The book also highlights some special types of transformers. By the end of this course, the students should be able to: (a) State the basics of electromagnetism, magnetic properties of materials, magnetic circuits, and electromagnetic induction; (b) Describe the construction, operation principles, and cooling methods of single-phase and three-phase power transformers; and (c) Describe the principles, functions, and applications of instrument transformers as electromagnetic induction based sensors. The book consists of four chapters. The first chapter presents the main topics required for understanding the structural, and operational principles of electromagnetic transformers. This chapter includes basics of magnetic fields, magnetic properties of materials, basics of the electromagnetism, and basics of the electromagnetic induction. The second chapter presents carefully selected details about the electromagnetic single-phase and three-phase power transformers. The chapter includes construction layouts, basics of transformer operation, transformer performance characteristics, and multi-winding transformers. The third chapter presents various cooling methods of transformers. In addition, detailed comparisons between the fields of applications of various practical cooling systems are provided. The fourth chapter focuses on the basic theories of instrument transformers and their applications of electromagnetic transformers in sensing applications.

Core Knowledge

By the end of this course, the students should be able to:

- Identify the magnetic properties of various materials.
- Explain the basic theories of electromagnetism, and electromagnetic induction.
- Describe the main constructional features of single-phase and three-phase power transformers.
- Explain the operation principles of power transformers.
- Identify the cooling methods of power transformers.
- Describe the basic principles of instrument transformers.
- State the applications of various types of transformers.

Core Skills

By the end of this course, students should be able to:

- Identify the required properties of materials used in the construction of various types of transformers.
- Enumerate the applications of various types of transformers.
- Identify the internal structures, and cooling methods of various types of power transformers.
- Estimate the basic operational characteristics and losses of instrument and power transformers.
- Perform the basic modeling and calculations of various types of sensor and power transformers.
- Specify potential and current transformers as sensors.
  - Specify suitable cooling method for a power transformer

Course Overview

Week	Topic
1	Magnetic properties of materials
2	Basics of electromagnetism
3	Basics of electromagnetic induction
4	Construction of single-phase power transformers
5-6	Operation principles of single-phase power transformers
7	Mid-term exam
8	Multi-winding single-phase power transformers
9	Cooling methods
10	Three-phase power transformers
11	Principles and applications of current sensing transformers
12	Principles and applications of voltage sensing transformers
13	Visit of a power distribution substation
14	Discussions
15	- (Final exam)

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Chapter 1

Fundamentals of Electromagnetism and Electromagnetic Induction

Objectives

By the end of this chapter, the following points will be covered

- The basics of magnetic fields,
- Magnetic properties of materials,
- The basics of the electromagnetism, and
- The basics of the electromagnetic induction.

Introduction

The operation of transformers is based on two basic principles. The first principle is the ***electromagnetism*** by which an electric current can produce a magnetic field. The second principle is the ***electromagnetic induction***, by which a time-varying magnetic field produced by a coil (called primary coil) can induce a voltage across the ends of another coil (called secondary coil) affected by that magnetic field. Changing the current in the primary coil changes the magnetic flux that is developed. The changing magnetic flux induces a voltage in the secondary coil. This chapter covers the basics of the magnetic fields, magnetic circuits, electromagnetism, and electromagnetic induction.

Magnetic Field

Magnetic fields can be either ***static*** (also called magnetostatic, or DC), or ***time-varying*** (also called AC, or magnetic waves). Both field types are space dependent, while the static fields are time independent and the time-varying fields are functions of time.

Static magnetic fields are constant fields, which do not change in intensity or direction over time, in contrast to low and high frequency alternating fields. Hence, they have a frequency of 0 Hz[1]. The magnetostatic fields are due to motion of electric charges with

[1] *They exert an attracting force on metallic objects containing, for example, iron, nickel or cobalt, and so magnets are commonly used for this purpose. In nature, the geomagnetic field of the earth exerts a force from south to north that allows, for example, the operation of a compass. Much stronger fields are generated by some types of industrial and medical equipment, such as in* ***Medical Resonance Imaging*** *(MRI) devices. The strength of a static magnetic flux density is expressed in Tesla (T) or in some countries in Gauss (G). The strength of the natural geomagnetic field varies from about 30 to 70 μT (1 μT is 10^{-6} T). Household magnets have strengths in the order of several tens of milli Tesla (1 mT = 10-3 T). By contrast, the fields of MRI equipment vary from between 1.5 to up to as much as 10 T.*

uniform velocity (direct current) or static magnetic charges (magnetic poles). On the other hand, time-varying fields or magnetic waves are usually due to accelerated charges or time-varying current. The magnetostatic fields cannot induce emf in a coil unless it is mechanically moved relative to the coil, while time-varying fields can induce an emf in coil without the need of moving the field source. Transformers are static machines that are based on the use of time-varying magnetic fields. The basic principles of magnetic fields are the same. In the following section, the main laws governing the magnetostatic fields will be presented for easily understanding the basics of magnetic fields. The time-varying fields have similar laws, but with much more details. On the other hands, the concepts are the same.

Magnetostatic fields

A ***permanent magnet*** is a piece of ferromagnetic material (see the next section on magnetic properties of materials), such as iron, which attracts other pieces of the same material. If a permanent magnet is suspended in the air so that it is free to swing in a horizontal plane, one end of the magnet will take up a position towards the earth's North Pole. This end is called the ***north seeking*** end or the ***north pole***, **N** of the magnet. Similarly the other end is known as the ***south seeking*** end or the ***south pole***, **S** of the magnet; see Fig. 1.

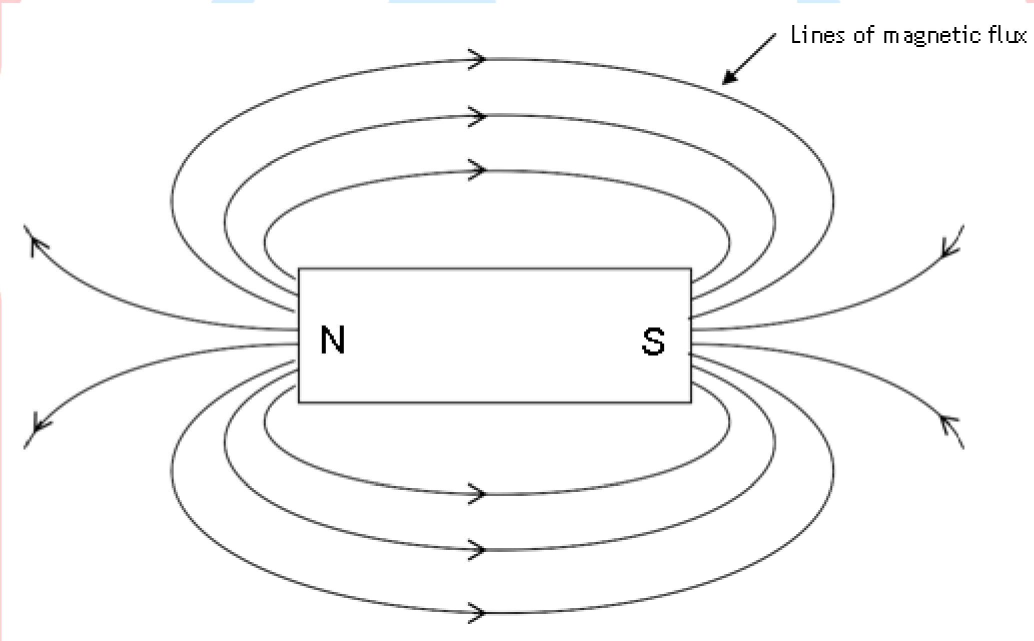


Fig. 1: Permanent magnet

The distribution of a magnetic field can be demonstrated by the following experiment. A permanent magnet is placed on a table, covered it by a sheet of cardboard and some iron filings are sprinkled uniformly over the sheet. A slight tapping of the cardboard will cause the filings to position themselves in curved lines between the poles as shown in Fig. 1. These curved lines can be used to visualize the magnetic condition of the space around the magnet, which may be identified as the ***magnetic field***. Also these lines lead to the idea of ***lines of magnetic flux*** which were introduced by **Michael Faraday** to visualize the distribution and density of the magnetic field. They can also be used as a vehicle to explain various effects of magnetism. It should be realized that the magnetic flux occupies the whole three-dimensional space in the vicinity of the magnet and decreases in strength as moved away from the magnet.

Each line of magnetic flux is a closed loop with no beginning and no end as shown in Fig. 1. In fact a flux line which starts at a point on the north pole of a magnet passes through the space surrounding it, enters the south pole and continues through the magnet to the starting point thus forming a closed loop. This follows that these lines never intersect.

When two magnets are arranged in such a way that unlike poles are next to each other, as shown in Fig. 2(a), attraction takes place. The lines of flux passing between the two magnets behave as if they were trying to shorten themselves causing the magnets to attract towards each other. If the magnets are arranged so that the like poles are near to each other, as shown in Fig. 2(b), then repulsion takes place. It is seen that the flux lines in the space between the two magnets are pointing in the same direction thus pushing the two magnets away from each other.

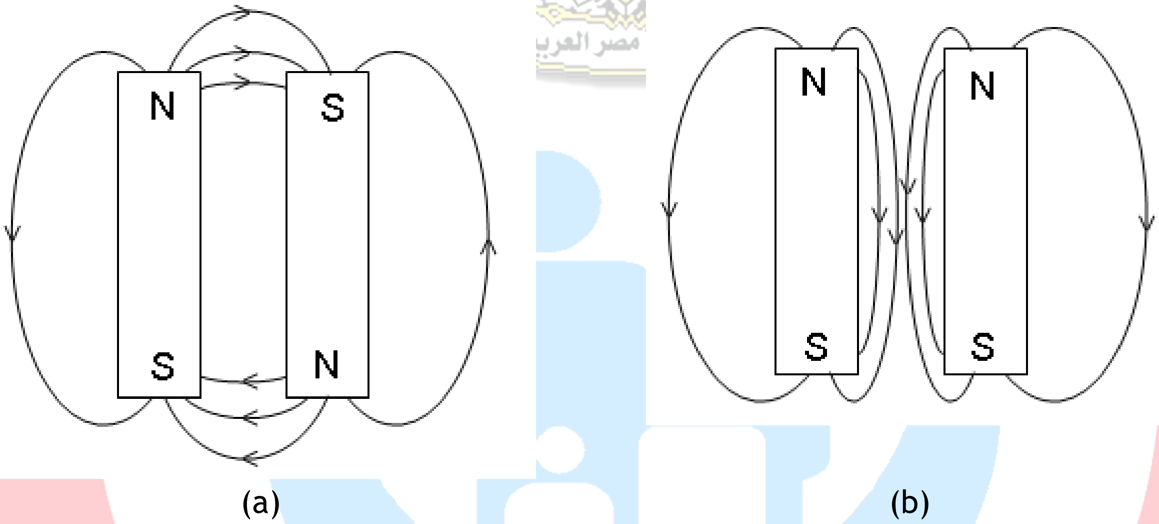


Fig. 2: Interaction between magnets. (a) Attraction; (b) Repulsion

The amount of magnetic field produced by a magnetic source is known as the **magnetic flux** and its symbol Φ. The unit of magnetic flux is the **weber** or **Wb**. The **Magnetic flux density (B)** is defined as the amount of flux per unit area, which is perpendicular to the direction of the flux. The unit of flux density is **tesla** or **T**. Therefore,

$$B = \frac{\Phi}{A} \qquad \text{Wb/m}^2, \text{Wb.m}^{-2} \text{ or tesla} \qquad (1)$$

where A is the area in m^2. It is seen from the equation that 1 T is equivalent to 1 $Wb/(m^2)$ which is another way of defining the units of flux density B.

Example 1

The magnetic flux crossing the air gap of the magnet shown in Fig. 3 is 12 mWb. Determine the flux density in the air gap if the magnet has dimensions shown.

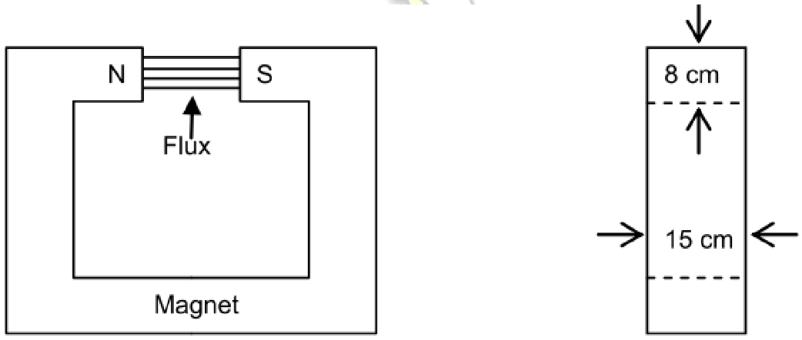


Fig. 3: Permanent magnet with an airgap

Solution

$$A = 8\times10^{-2}\times15\times10^{-2} = 120\times10^{-4}\ m^2 = 0.012\ m^2$$

This gives

$$B = \frac{\Phi}{A} = \frac{12mWb}{0.012} = \frac{0.012}{0.012} = 1\,T$$

Magnetic field due to an electric current

A fundamental law of electromagnetism is that a magnetic field is produced around a conductor when that conductor carries an electric current. This phenomenon was demonstrated by Oersted in 1820. He noticed that when a wire carrying an electric current is placed above a magnetic needle, the needle was deflected clockwise or anticlockwise depending on the direction of the current flow. Using his observations it is possible to form a basic sign convention to indicate the direction of the magnetic field.

Consider a wire carrying an electric current which has a cross section as shown in Fig. 4. In Fig. 4(a) the current is flowing into the paper as indicated by the cross. The magnetic field has a clockwise direction and the concentric circles around the wire show the flux lines. Another method of representing this is to place a corkscrew along the conductor, which travels into the paper when rotated clockwise. The movement of the corkscrew into the paper represents the current flow and the clockwise rotation indicates the direction of the magnetic field. In Fig. 4(b) the current flow is reversed, i.e. flowing out of the paper, which is indicated by the dot. In this case it is obvious that the direction of the field is anticlockwise and again flux lines are shown by the concentric circles.

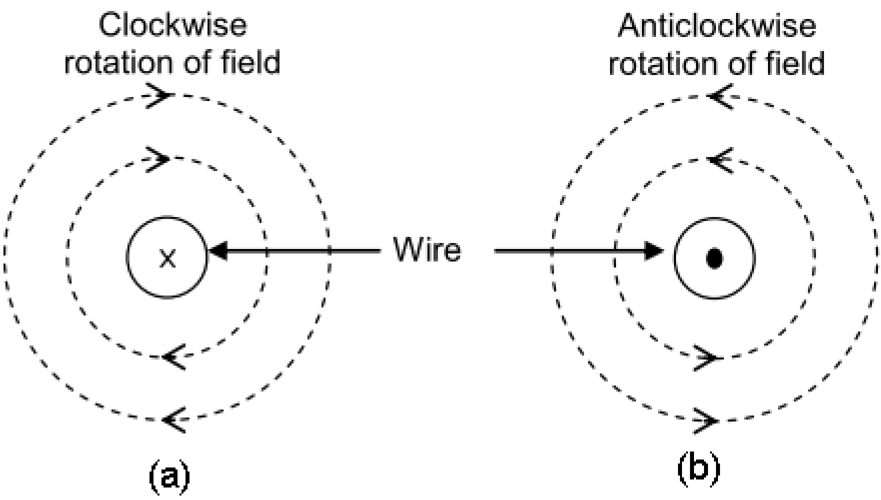


Fig. 4: Sign convention of electromagnetic field

Ampere's Law

The Ampere's Law is particularly useful in determining magnetic field strength near current carrying conductors in certain geometrical arrangements. Knowing the field strength the magnetic flux density at a point and the magnetic flux around a circuit can easily be determined. In electrical engineering problems such as electrical machines, transformers etc, we are often asked to design a magnetic circuit to produce a given flux. The application of the law is straight forward provided that we know the direction of the flux and the law is most suitable in situations where the field patterns are predictable.

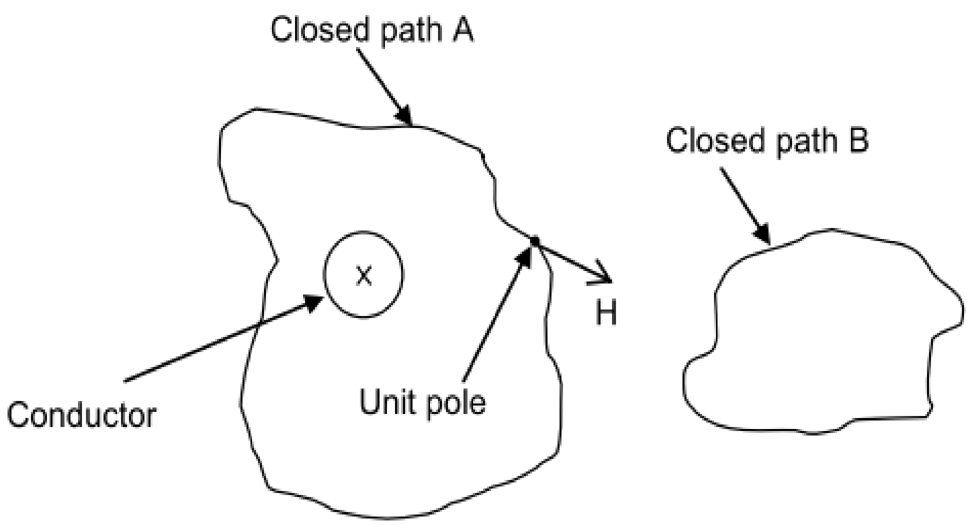


Fig. 5: Closed path enclosing a current carrying conductor

The Ampere's law is a statement of fact based on experiments. If a unit pole is placed on any irregular closed path, such as path A in Fig. 5, enclosing a current carrying conductor, it experiences a force H, which is tangential to the path, as shown in Fig. 5. When the unit pole is moved an infinitely small distance δℓ along the path the work done is the product of H and ℓ. The Ampere's law states that the sum of the product of H ℓ, which is the total work done by the unit pole in moving once around the closed path A enclosing the conductor is numerically equal to the current flow in the conductor. This is written as

$$\sum_{0}^{\ell} H\delta\ell = I \quad (A) \qquad (2)$$

In the limit as δℓ tends to zero this summation becomes an integral and is written as

$$\oint_{0\to\ell} H\delta\ell = I \quad (A) \qquad (3)$$

The circle around the integral sign indicates that the integration is done around a closed path. If the unit pole is moved around any path, regular or irregular, which encloses the conductor will produce the same result. However path B in Fig. 5 fails to link the conductor and therefore no work is done in moving a unit pole round such a path.

The Ampere's law is very simple to use when the tangential force H is a constant and this is the case for all examples considered here. Thus if H is constant then (3) becomes

$$H\oint_{0\to\ell}\delta\ell = H\ell = I \ (A)$$
$$\Rightarrow H = \frac{I}{\ell} \quad (A/m) \qquad (4)$$

This force H is called the ***magnetizing force*** or the ***magnetic field strength***. As an example it is required to calculate the magnitude of the field strength at a point distance r from the axis of a long conductor carrying a current I. The field pattern for such a case is shown in Fig. 4 and if we consider a circular path at radius r, the field strength along this path is tangential to the path and will be constant (as the field strength at any point on a flux line is constant). From Fig. 6 and Fig. 4, the field strength H at a distance r is given as

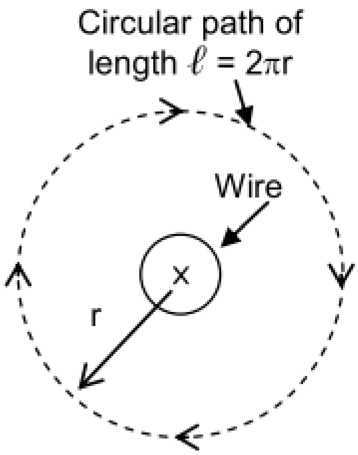


Fig. 6: Circular path around a current carrying conductor

$$H = \frac{I}{\ell} = \frac{I}{2\pi r} \quad (A/m) \qquad (5)$$

Magnetomotive force mmf F_m

In an electric circuit the current is due to the existence of an ***electromotive force***. In a similar manner the magnetic flux in a magnetic circuit is due to the existence of a ***magnetomotive force*** *mmf* or F_m, caused by a current flowing through one or more turns. Thus a coil, as shown Fig. 7, of N turns carrying a current of I Amps is the basic force for the creation of magnetic fields.

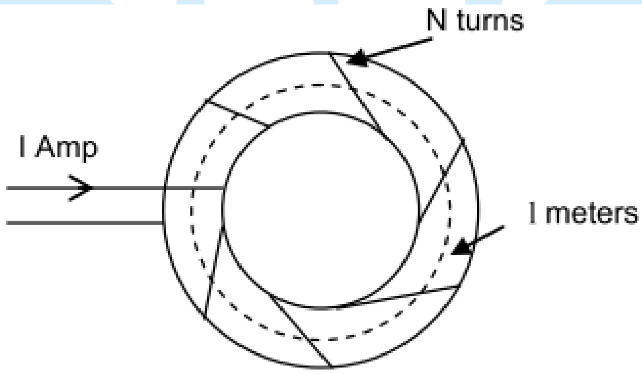


Fig. 7: A coil with N turns

Therefore we can write an equation for F_m as

$$mmf\ F_m = NI \qquad (\text{ampere - turns or AT}) \qquad (6)$$

and has the units ampere-turns. Since N has no units sometimes it is expressed in amperes.

The magnetomotive force is the total current linked with the ***magnetic circuit***. If the magnetic circuit has a uniform cross section, the magnetomotive force per unit length of the magnetic ircuit is the magnetizing force or magnetic field strength. As shown Fig. 7 if ℓ is the mean length (meters) of the magnetic circuit then magnetic field strength H is given as

$$H = \frac{NI}{\ell} \qquad (A/m) \qquad (7)$$

Example 2

A circular wooden ring (Fig. 7) of mean diameter 20 cm has a coil of 800 turns uniformly wound around it. If the magnetic field strength is 5000 A/m calculate the current in the coil.

Solution

The mean length (circumference) of the wooden ring is $\ell = \pi d = \pi \times 20 \times 10^{-2}$ m and from we have

$$I = \frac{H\ell}{N} = \frac{5000 \times \pi \times 20 \times 10^{-2}}{800} = \frac{10\pi}{8} = 3.93\,A$$

Permeability and B-H curves

For free space or a non-magnetic material the ratio of magnetic flux density B to magnetic field strength or magnetizing force H is a constant. This constant is known as *the **permeability for free space*** and has the symbol μ_0 i.e.

$$\mu_0 = \frac{B}{H} = 4\pi \times 10^{-7} \qquad \left(\frac{Wb/m^2}{AT/m} \Rightarrow \frac{Wb}{mAT}\right) \quad (8)$$

Note that this constant has a numerical value of $4\pi \times 10^{-7}$ Wb/(mAT) as given (8). Another unit for this constant is henrys/m and the interested reader can look elsewhere for details (see the list of references at the end of the book). All non-magnetic materials are considered to have the same permeability as free space. Fig. 8 shows a graph of flux density B plotted against the magnetic field strength H for free space known as a ***B-H curve***. This curve is linear and the slope of the straight line is μ_0.

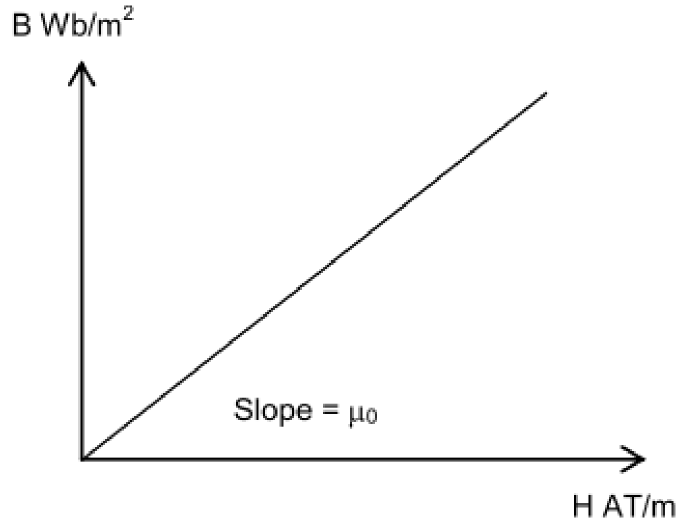


Fig. 8: B-H curve for free space

Example 3

A coil of 200 turns is wound uniformly over a wooden ring having a mean circumference of 60 cm and a uniform cross sectional area of 5 cm^2. If the current through the coil is 4 A calculate (a) the magnetic field strength (b) the flux density and (c) the total flux.

Solution

Here N = 200, I = 4 A, cross sectional area A = 5 cm^2 = 5×10^{-4} m^2 and the mean circumference $\ell = 60\times10^{-2}$ m.

(a) $$H = \frac{NI}{\ell} = \frac{200\times4}{60\times10^{-2}} = \frac{2000\times4}{6} = 1333 \quad A/m$$

(b) As the wooden ring is made of a non-magnetic material

$$B = \mu_0 H = 4\pi\times10^{-7}\times1333 = 1675\times10^{-6} = 1675\ \mu T$$

(c) $$\Phi = BA = 1675\times10^{-6}\times5\times10^{-4} = 0.1675\times5\times10^{-6} = 0.8375\ \mu Wb$$

Example 4

Calculate the magnetomotive force required to produce a flux of 0.015 Wb across an air gap 2.5 mm long, having an effective area of 30 cm^2.

Solution

Area A of the air gap is

$$A = 30\ cm^2 = 30\times10^{-4}\ m^2$$

flux density B is

$$B = \frac{\Phi}{A} = \frac{0.015}{30\times10^{-4}} = \frac{0.015\times10^4}{30} = \frac{150}{30} = 5\ T$$

magnetic field strength H is

$$H = \frac{B}{\mu_0} = \frac{5}{4\pi\times10^{-7}} = 0.398\times10^7\ A/m$$

Therefore mmf is

$$mmf = NI = H\ell = 0.398\times10^7\times2.5\times10^{-3} = 0.9947\times10^4 = 9947\ AT$$

Magnetic Properties of Materials

All matter is composed of atoms and atoms are composed of protons, neutrons and electrons. The protons and neutrons are located in the atom's nucleus and the electrons are in “constant motion” around the nucleus. Electrons carry a negative electrical charge and produce a magnetic field as they move through space. A magnetic field is produced whenever an electrical charge is in motion.

This may be hard to visualize on a subatomic scale but consider an electric current flowing through a conductor. When the electrons (electric current) are flowing through the conductor, a magnetic field forms around the conductor. The magnetic field can be detected using a compass.

Since all matter is comprised of atoms, all materials are affected in some way by a magnetic field. However, not all materials react the same way. When a material is placed within a magnetic field, the material's electrons will be affected. However, materials can react quite differently to the presence of an external magnetic field. This reaction is dependent on a number of factors such as the atomic and molecular structure of the material, and the net magnetic field associated with the atoms. In most atoms, electrons occur in pairs. Each electron in a pair spins in the opposite direction, so when electrons are paired together, their opposite spins cause their magnetic fields to cancel each other. Therefore, no net magnetic field exists. Alternately, materials with some unpaired electrons will have a net magnetic field and will react more to an external field. Most materials can be classified as ***ferromagnetic***, ***diamagnetic***, or ***paramagnetic***.

The relation between the magnetic flux density (B) and the magnetic field strength (H) is generally given as a function of the permeability of free space (μ_o), the susceptibility (χ_m), or the relative permeability (μ_r) or the absolute permeability (μ) as,

$$B = H\,\mu_o(1+\chi_m) = H\,\mu_o\mu_r = H\mu \quad (9)$$

- ***Diamagnetic materials ($\chi_m < 1$)***

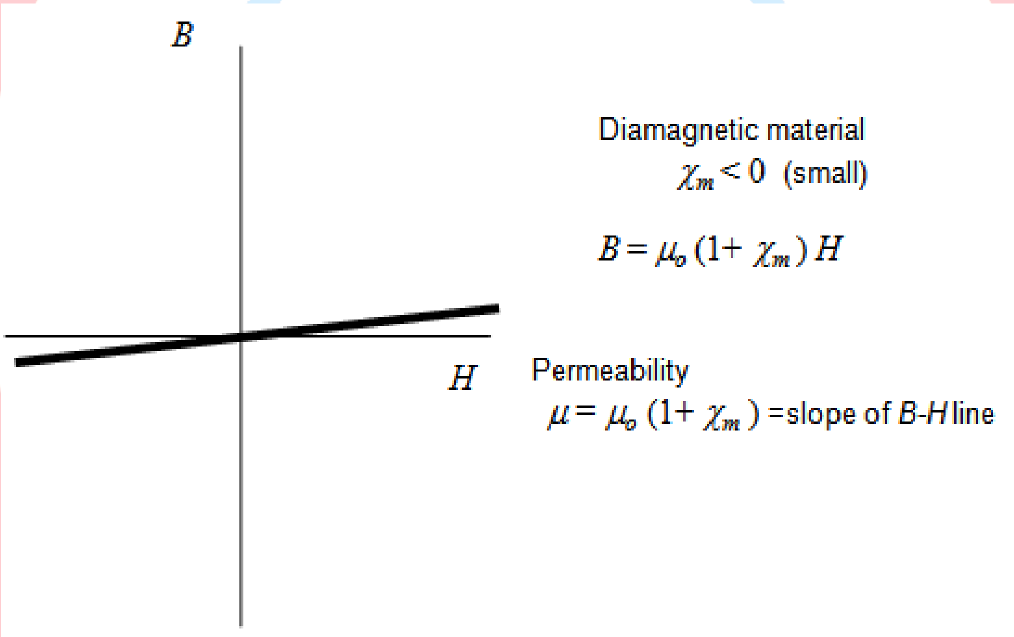


Fig. 9: B-H curve of a diamagnetic material

- Small and negative susceptibility.
- Slightly repelled by a magnetic field.
- Do not retain the magnetic properties when the external field is removed.
- Magnetic moment - opposite direction to applied magnetic field.
- Solids with all electrons in pairs - no permanent magnetic moment per atom.
- Properties arise from the alignment of the electron orbits under the influence of an external magnetic field.
- Most elements in the periodic table, including copper, silver, and gold, are diamagnetic. Example, χ_m(argon) ~ -1.0×10^{-8}, and χ_m(copper) ~ -1.0×10^{-5}
- The B-H curve of a diamagnetic material is shown in Fig. 9.

- **Paramagnetic materials (χ_m slightly > 1)**

- Small and positive susceptibility.
- Slightly attracted by a magnetic field.
- Material does not retain the magnetic properties when the external field is removed.
- Properties are due to the presence of some unpaired electrons and from the alignment of the electron orbits caused by the external magnetic field.
- Examples - magnesium, molybdenum, lithium, and tantalum. Example, χ_m(oxygen) ~ 2.0×10^{-6}, and χ_m(aluminum) ~ 2.1×10^{-5}
- The B-H curve of a diamagnetic material is shown in Fig. 10.

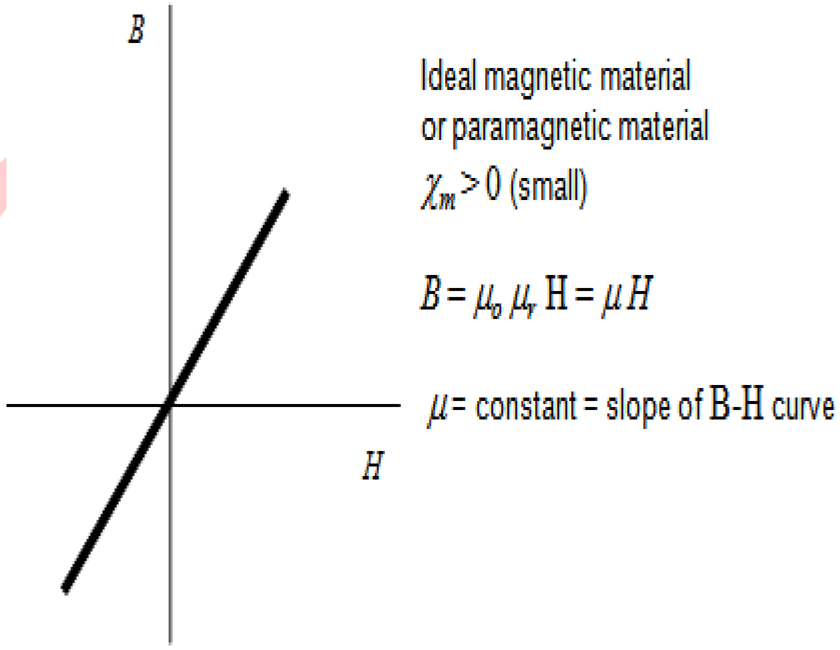


Fig. 10: B-H curve of a paramagnetic material

- **Ferromagnetic materials ($\chi_m \gg 1$)**
  - Large and positive susceptibility.
  - Strong attraction to magnetic fields.
  - Retain their magnetic properties after the external field has been removed.
  - Some unpaired electrons so their atoms have a net magnetic moment.
  - Strong magnetic properties due to the presence of magnetic domains. In these domains, large numbers of atomic moments (10^{12} to 10^{15}) are aligned parallel so that the magnetic force within the domain is strong. When a ferromagnetic material is in the un-magnetized state, the domains are nearly randomly organized and the net magnetic field for the part as a whole is zero. When a magnetizing force is applied, the domains become aligned to produce a strong magnetic field within the part.
  - Iron, nickel, and cobalt are examples of ferromagnetic materials.
  - Magnetization is not proportional to the applied field. Example, χ_m(ferrite) ~ 100, and χ_m(iron) ~ 1000
  - The B-H curves of some ferromagnetic materials are shown in Fig. 11.

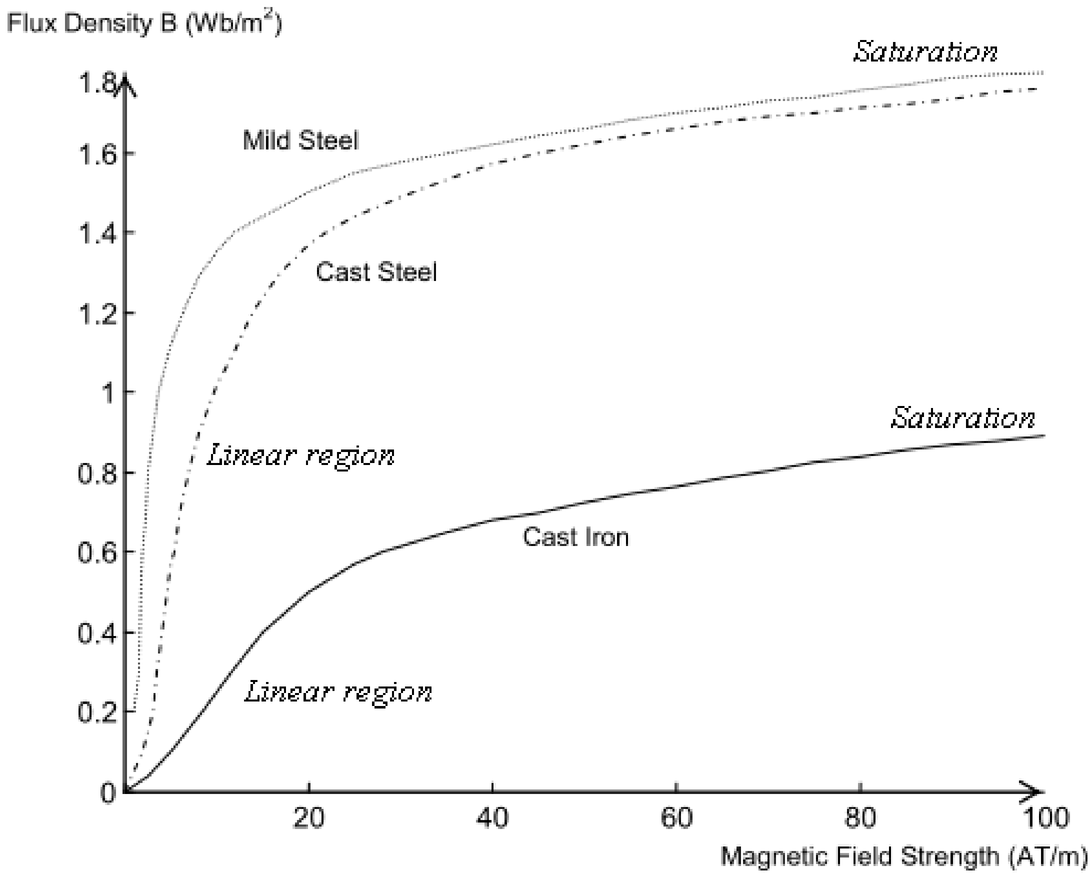


Fig. 11: B-H curves of some ferromagnetic materials

Ferromagnetic materials get their magnetic properties not only because their atoms carry a magnetic moment but also because the material is made up of small regions known as ***magnetic domains***. In each domain, all of the atomic dipoles are coupled together in a preferential direction. This alignment develops as the material develops its crystalline structure during solidification from the molten state. Magnetic domains can be detected using Magnetic Force Microscopy (MFM) and images of the domains like the one shown below in Fig. 12 can be constructed.

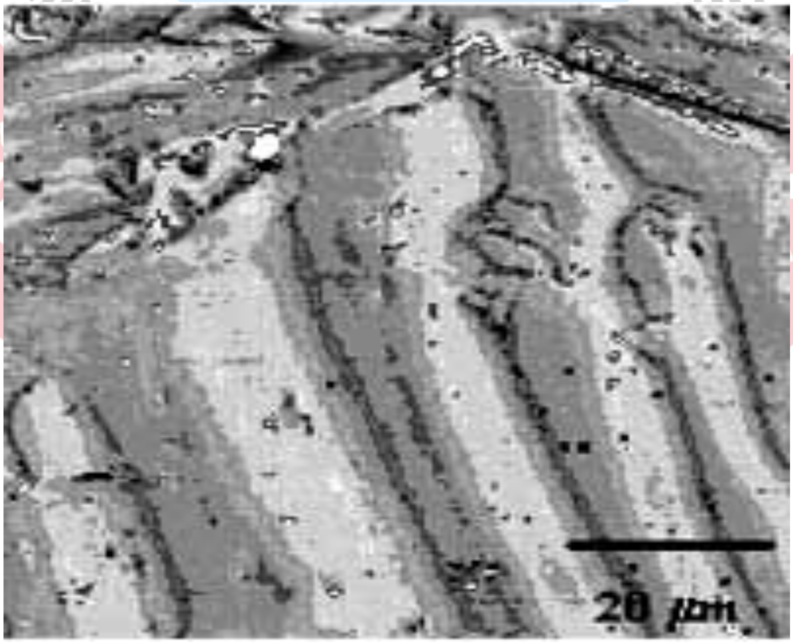
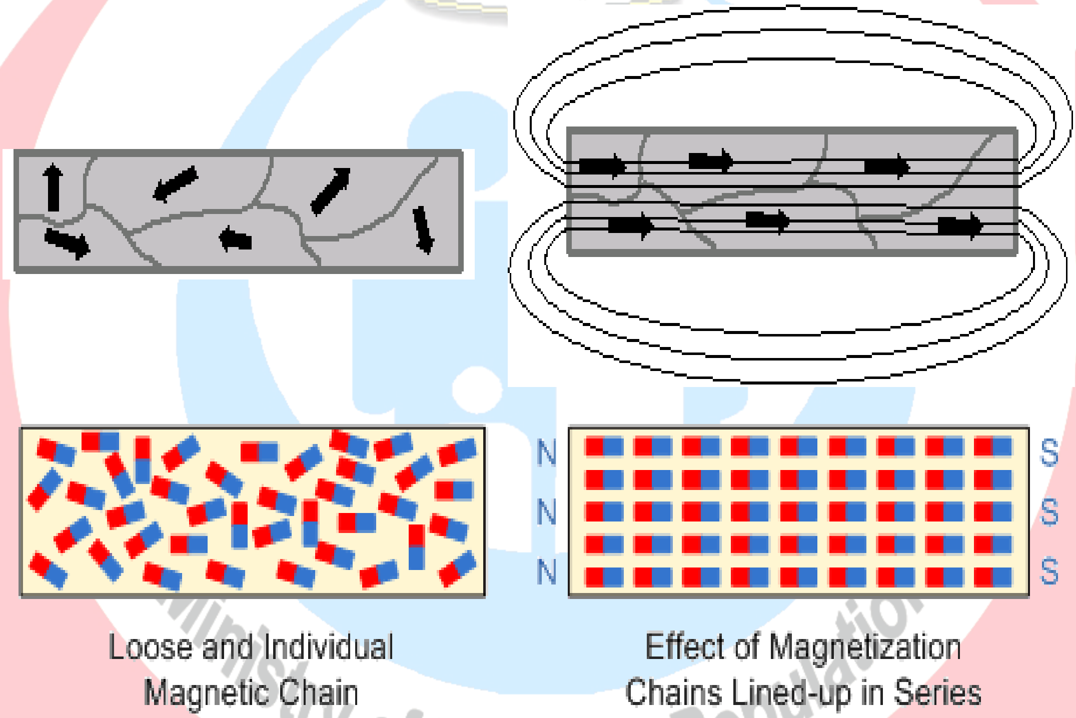


Fig. 12: Magnetic Force Microscopy (MFM) image showing the magnetic domains in a piece of

heat-treated carbon steel.

During solidification a trillion or more atom moments are aligned parallel so that the magnetic force within the domain is strong in one direction. Ferromagnetic materials are said to be characterized by "spontaneous magnetization" since they obtain saturation magnetization in each of the domains without an external magnetic field being applied. Even though the domains are magnetically saturated, the bulk material may not show any signs of magnetism because the domains develop themselves are randomly oriented relative to each other.

Ferromagnetic materials become magnetized when the magnetic domains within the material are aligned; Fig. 13. This can be done my placing the material in a strong external magnetic field or by passes electrical current through the material. Some or all of the domains can become aligned. The more domains that are aligned, the stronger the magnetic field in the material. When all of the domains are aligned, the material is said to be magnetically saturated. When a material is magnetically saturated, no additional amount of external magnetization force will cause an increase in its internal level of magnetization (see Fig. 11).



(a) Unmagnetized Material (b) Magnetized Material

Fig. 13: Magnetization of a ferromagnetic material

A great deal of information can be learned about the magnetic properties of a material by studying its ***hysteresis loop***. A hysteresis loop shows the relationship between the induced magnetic flux density B and the magnetizing force H. It is often referred to as the B-H loop. An example hysteresis loop is shown in Fig. 14.

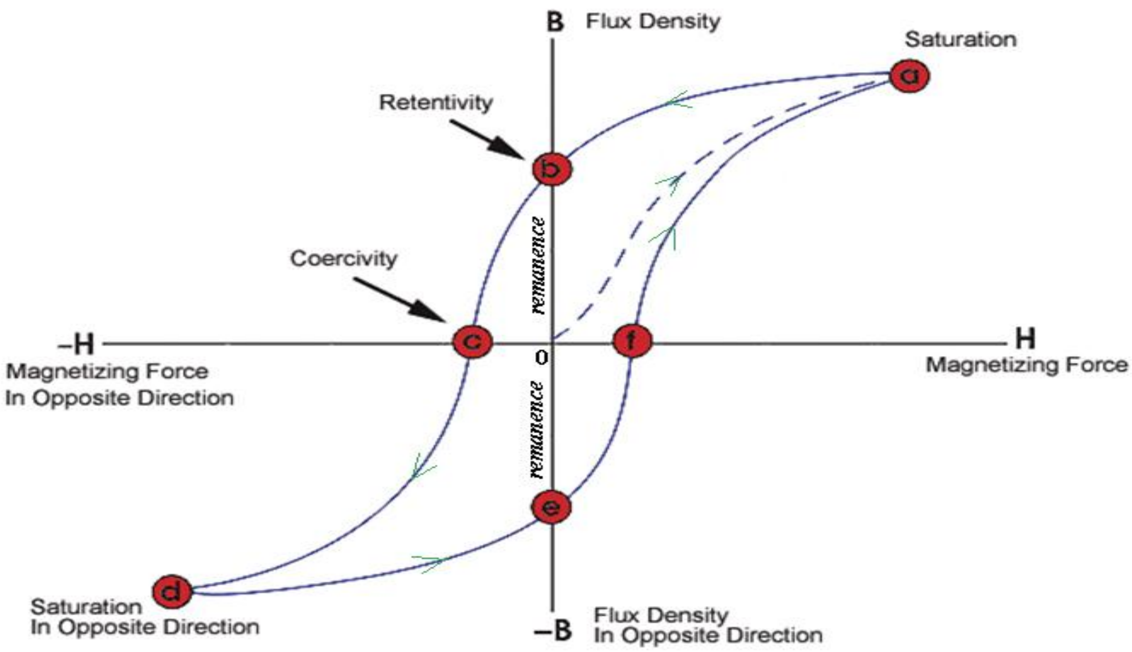
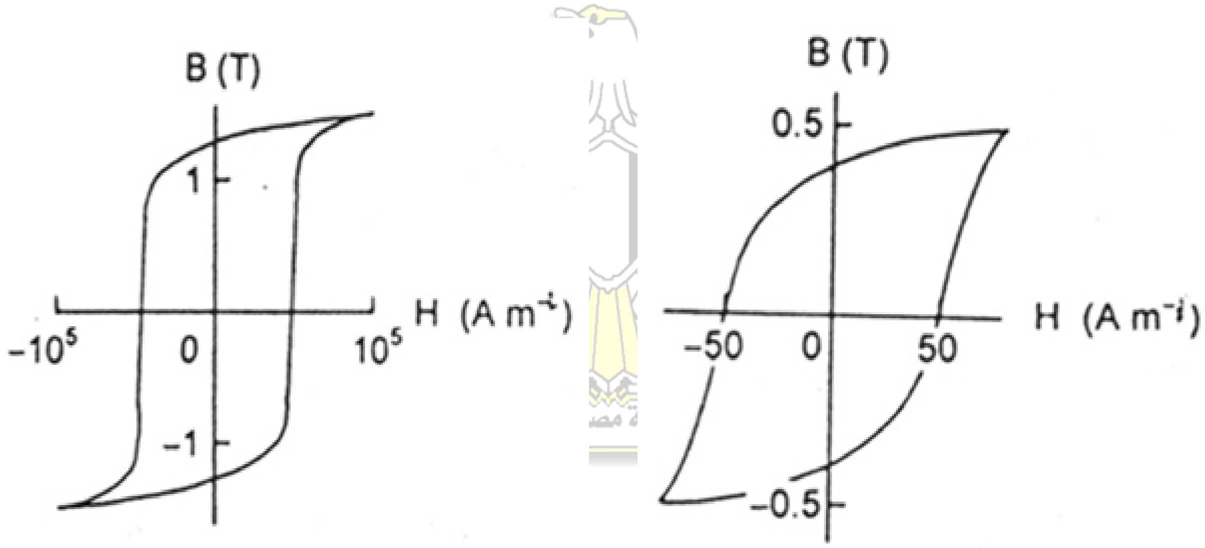


Fig. 14: Hysteresis loop of a ferromagnetic material

The loop is generated by measuring the magnetic flux B of a ferromagnetic material while the magnetizing force H is changed. A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line 0 → a as H is increased. As the line demonstrates, the greater the amount of current applied (H+), the stronger the magnetic field in the component (B+). At point a almost all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little increase in magnetic flux. The material has reached the point of ***magnetic saturation***.

When H is reduced back down to zero, the curve will move from point a to point b. At this point, it can be seen that some magnetic flux density remains in the material even though the magnetizing force is zero. This is referred to as the point of ***retentivity*** on the graph and indicates the ***remanence*** or level of residual magnetism in the material. Some of the magnetic domains remain aligned but some have lost their alignment. As the magnetizing force is reversed, the curve moves to point c, where the magnetic flux density has been reduced to zero. This is called the point of ***coercivity*** on the curve. The reversed magnetizing force has flipped enough of the domains so that the net magnetic flux density within the material is zero. The H-field required to remove the residual magnetism from the material, is called the ***coercive force*** or ***coercivity*** of the material.

As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the opposite direction (point d). Reducing H to zero brings the curve to point e. It will have a level of residual magnetism equal to that achieved in the other direction. Increasing H back in the positive direction will return B to zero. Notice that the curve did not return to the origin of the graph because some H-field is required to remove the residual magnetism. The curve will take a different path from point f back the saturation point where it with complete the loop. The area enclosed by the hysteresis loop is called the hysteresis losses, which is in the form of heat energy.



(a) (b)

Fig. 15: Hysteresis loop of (a) hard magnetic material, and (b) soft magnetic material

The shape of the hysteresis loop tells a great deal about the material being magnetized. The hysteresis curves of two different materials are shown in the graphs of Fig. 15. In the "hard" magnetic materials, H_c (coercivity) is high, area of the loop is large, used for permanent magnets. In the "soft" magnetic materials, H_c is small, area of loop is small, used for transformer cores and electromagnets.

Reluctance (ℜ) and the magnetic circuit

In an electric circuit an ***electromotive force*** or an **emf** (E) will force a current I to flow in the circuit and the opposition to the flow of current is the ***resistance*** (R). In a similar manner a ***magnetomotive force*** or **mmf** (F_m) will force a magnetic flux (Φ) to flow in a magnetic circuit and the opposition to the flow of flux is the ***reluctance*** (ℜ). This is illustrated in Fig. 16.

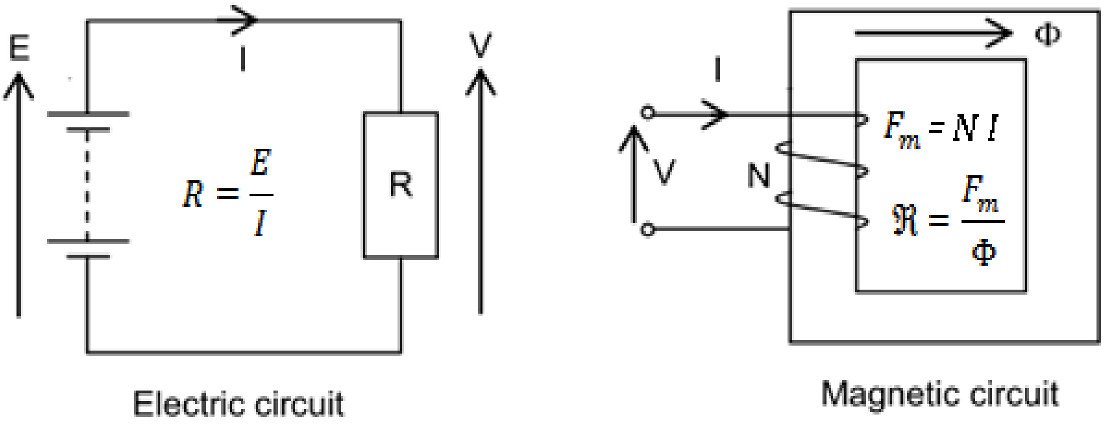


Fig. 16: Analogy between magnetic and electric circuits

Table 1: Electric and magnetic circuit parameters

Electric circuit		Magnetic circuit	
Quantity	Units	Quantity	Units
Emf (E)	Volt(V)	Mmf (F_m)	Ampere turns(AT)
Electric field strength (E)	Volts per meter (V/m)	Magnetic filed strength (H)	Ampere turns per meter (AT/m)
Current (I) Equivalent to emf per resistance	Ampere (A)	Magnetic flux ( ) Equivalent to mmf per reluctance	Weber (Wb)
Current density	Ampere per squared meter (A/m^2)	Flux density (B)	Tesla or Weber per squared meter (Wb/m^2)
Resistance (R)	Ohm ( )	Reluctance (S)	Ampere turns per Weber (AT/Wb)

For the electric circuit shown in Fig. 16, the emf E is equivalent to the volt drop across the resistor R. The analogy for the magnetic circuit is that the mmf F_m is equivalent to the product of the flux and the reluctance.

It is helpful to present various electric and magnetic quantities and their relationship in tabular form and such a table is given in Table 1. It is noted that the same symbol E is used to denote the electromotive force emf and the electric filed strength, which may be confusing at times. Normally bold letter E is used to represent the electric filed strength and care must be taken in using this symbol.

Ministry of Health & Population

Example 5

The radius and the cross sectional area of a mild steel ring are 5 cm and 400 mm^2 respectively. A current of 0.5 A flows in a coil wound around the ring and the flux produced is 0.1 mWb. Calculate (a) the reluctance $\Re$ of mild steel and (b) the number of turns of the coil if the relative permeability is 200.

Solution

Here

Length of the ring ℓ = $2\pi r = 2\pi(5\times10^{-2})$ m,
Cross sectional area A = 400×10^{-6} m^2
Current I in the coil = 0.5 A
Flux Φ = 0.1×10^{-3} Wb
Relative permeability μ_r = 200

(a)

$$\Re = \frac{\ell}{\mu_0\mu_r A} = \frac{2\pi\times5\times10^{-2}}{4\pi\times10^{-7}\times200\times400\times10^{-6}}$$

$$= \frac{5\times10^{-2}}{2\times10^{-7}\times2\times4\times10^{-2}} = \frac{5\times10^{7}}{16} = 3.125\times10^{6}\ AT/Wb$$

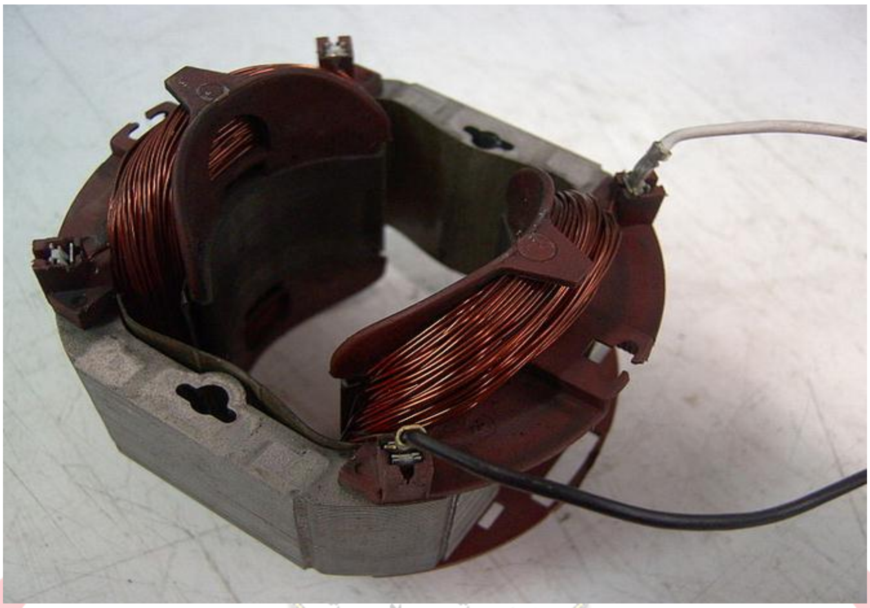
(b)

$$F_m = \Re\Phi = 3.125\times10^{6}\times0.1\times10^{-3} = 0.3125\times10^{3} = 312.5 \quad (AT)$$

Time-varying magnetic fields

It is essentially to know that the frequency of a magnetic field wave is the same as the frequency of the source current that produces the field. Therefore, DC currents produce DC magnetic or magnetostatic fields, while AC currents produce AC or time-varying fields. The operation of transformers is based on the time-varying magnetic fields. Time-varying magnetic fields can be produced using either a mechanically moved magnetostatic field, or an electromagnetic coil supplied with AC current. The former method is used in DC machines, while the later method is used in AC machines such as transformers.

An electromagnetic coil is an electrical conductor such as a wire in the shape of a coil, spiral or helix as shown in Fig. 17. Electromagnetic coils are used in electrical engineering, in applications where electric currents interact with magnetic fields, in devices such as electric motors, generators, inductors, electromagnets, transformers, and sensor coils. Either an electric current is passed through the wire of the coil to generate a magnetic field, or conversely an external time-varying magnetic field through the interior of the coil generates an EMF (voltage) in the conductor.



(a)

(b)

Fig. 17: Electromagnetic coils of (a) a motor, (b) a transformer

A current through any conductor creates a circular magnetic field around the conductor due to Ampere's law; Fig. 18. The advantage of using the coil shape is that it increases the strength of magnetic field produced by a given current. The magnetic fields generated by the separate turns of wire all pass through the center of the coil and add (superpose) to produce a strong field there. The more turns of wire, the stronger the field produced. Conversely, a changing external magnetic flux induces a voltage in a conductor such as a wire, due to Faraday's law of induction. The induced voltage can be increased by winding the wire into a coil, because the field lines intersect the circuit multiple times.

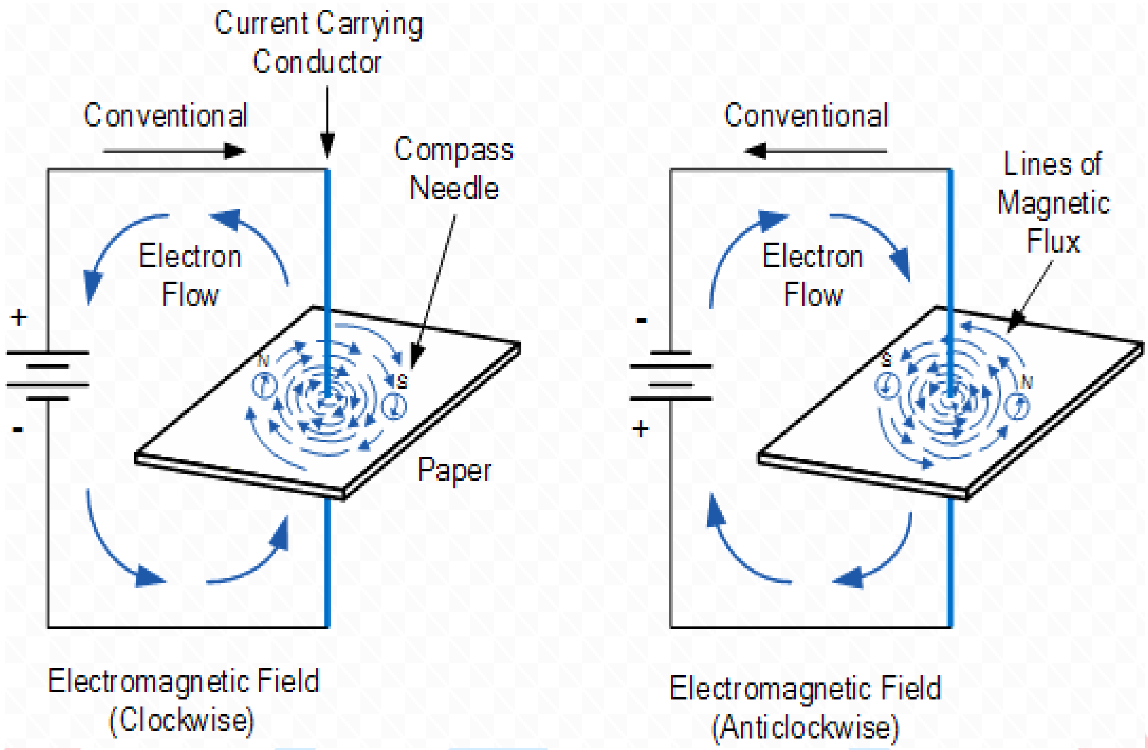


Fig. 18: Magnetic field around a conductor under DC current, and effect of current polirty changes

Electromagnetic Induction

When a conductor is moved across a magnetostatic field so as to cut through the lines of force (or flux), an electromotive force (e.m.f.) is produced in the conductor (Fig. 19(a)). This equivalent to subjecting the same conductor to a time-varying magnetic field (i.e. produced by AC current), but in this case the e.m.f is produced without the need of moving the conductor across the magnetic field (Fig. 19(b)); this called the transformer action. The reason is that the time-varying field has a non-zero rate of change even if its producing source and the conductor are fixed (i.e. static).

In both situations, if the conductor forms part of a closed circuit then the produced e.m.f causes an electric current to flow around the circuit. Hence an e.m.f. (and thus current) is 'induced' in the conductor as a result of the electromagnetic induction. This effect is known as 'electromagnetic induction'.

For example, consider Fig. 20(a) where a coil of wire connected to a centre-zero galvanometer, which is a sensitive ammeter with the zero-current position in the centre of the scale. This example can also be considered as an analogy of the effects of time-varying magnetic fields.

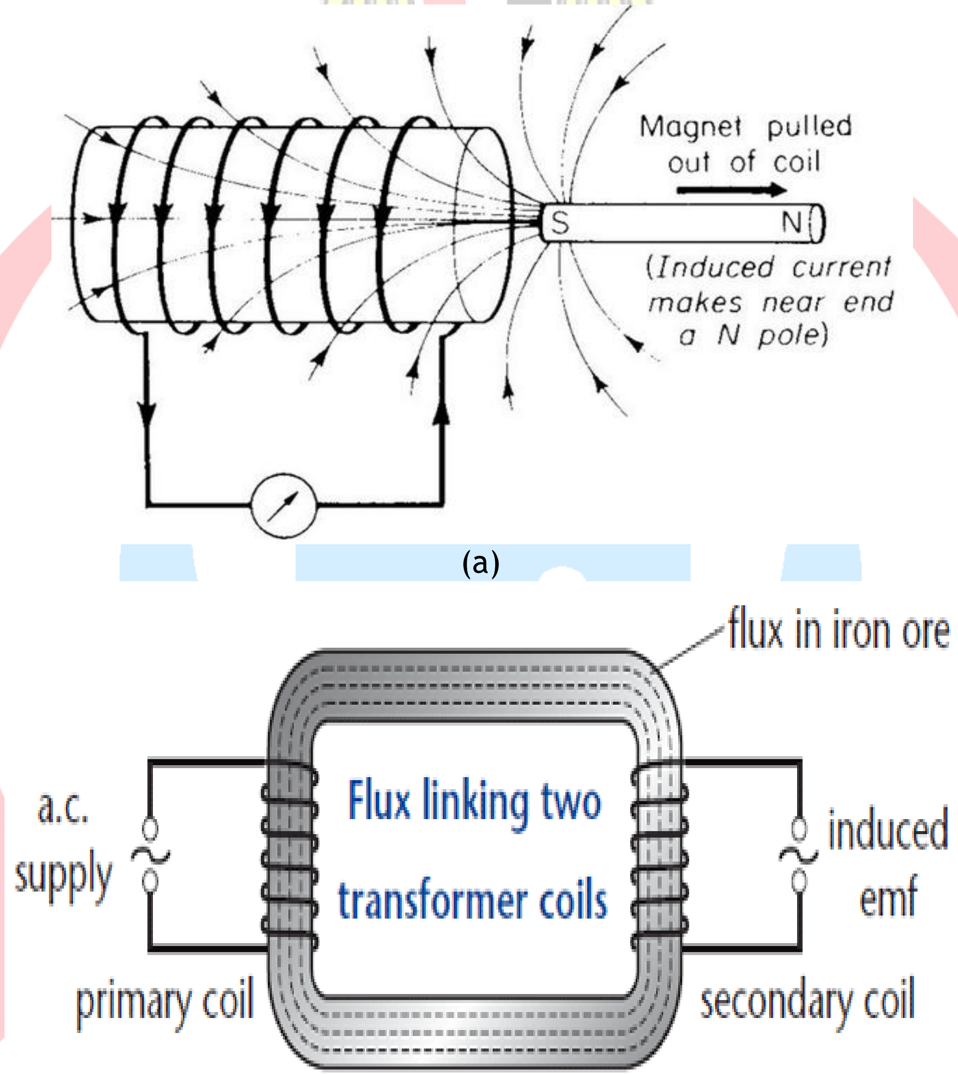


Fig. 19: Basic electromagnetic induction phenomena. (a) via magnetostatic field; (b) via time-varying magnetic field

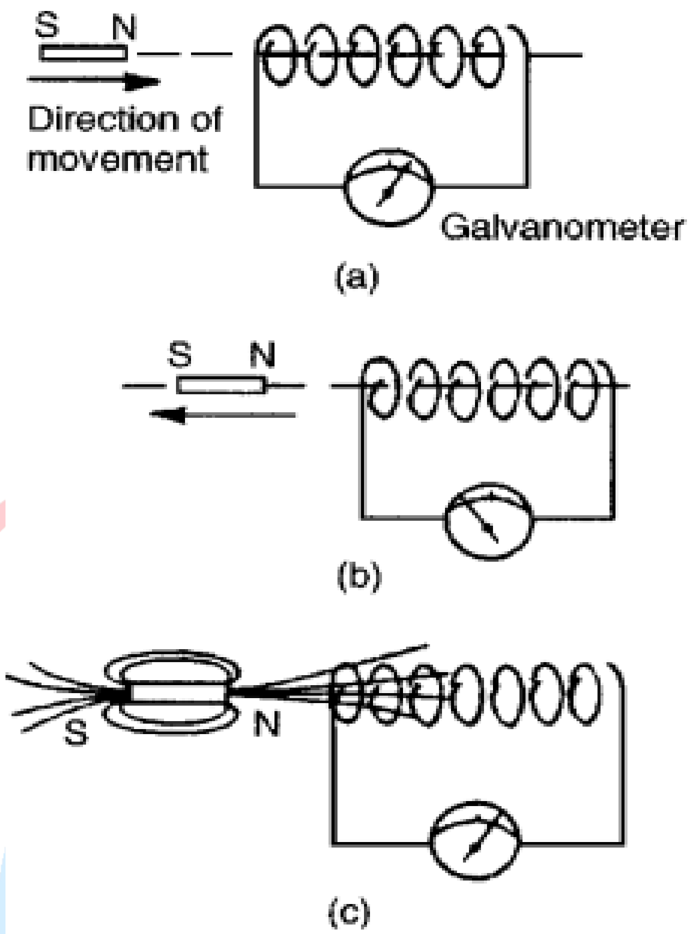


Fig. 20: Electromagnetic induction by a magnetostatic source of magnetic field

a) When the magnet is moved at constant speed towards the coil (Fig. 20(a)), a deflection is noted on the galvanometer showing that a current has been produced in the coil.
b) When the magnet is moved at the same speed as in (a) but away from the coil the same deflection is noted but is in the opposite direction (see Fig. 20(b))
c) When the magnet is held stationary, even within the coil, no deflection is recorded.
d) When the coil is moved at the same speed as in (a) and the magnet held stationary the same galvanometer deflection is noted.
e) When the relative speed is, say, doubled, the galvanometer deflection is doubled.
f) When a stronger magnet is used, a greater galvanometer deflection is noted.
g) When the number of turns of wire of the coil is increased, a greater galvanometer deflection is noted.

Fig. 20(c) shows the magnetic field associated with the magnet. As the magnet is moved towards the coil, the magnetic flux of the magnet moves across, or cuts, the coil. It is the relative movement of the magnetic flux and the coil that causes an e.m.f. and thus current, to be induced in the coil. This effect is known as electromagnetic induction. The laws of electromagnetic induction stated in section 9.2 evolved from experiments such as those described above.

Faraday's Law of Induction

From the above description we can say that a relationship exists between an electrical voltage and a changing magnetic field to which Michael Faraday's famous law of

Ministry of Health & Population

electromagnetic induction states: “*that a voltage is induced in a circuit whenever relative motion exists between a conductor and a magnetic field and that the magnitude of this voltage is proportional to the rate of change of the flux*”. In other words, Electromagnetic Induction is the process of using magnetic fields to produce voltage, and in a closed circuit, a current. So how much voltage (emf) can be induced into the coil using just magnetism? Well this is determined by the following 3 different factors.

1) Increasing the number of turns of wire in the coil – By increasing the amount of individual conductors cutting through the magnetic field, the amount of induced emf produced will be the sum of all the individual loops of the coil, so if there are 20 turns in the coil there will be 20 times more induced emf than in one piece of wire.
2) Increasing the speed of the relative motion between the coil and the magnet – If the same coil of wire passed through the same magnetic field but its speed or velocity is increased, the wire will cut the lines of flux at a faster rate so more induced emf would be produced.
3) Increasing the strength of the magnetic field – If the same coil of wire is moved at the same speed through a stronger magnetic field, there will be more emf produced because there are more lines of force to cut.

If we were able to move the magnet in the diagram above (Fig. 2) in and out of the coil at a constant speed and distance without stopping we would generate a continuously induced voltage that would alternate between one positive polarity and a negative polarity producing an alternating or AC output voltage and this is the basic principle of how an electrical generator works similar to those used in dynamos and car alternators.

In small generators such as a bicycle dynamo, a small permanent magnet is rotated by the action of the bicycle wheel inside a fixed coil. Alternatively, an electromagnet powered by a fixed DC voltage can be made to rotate inside a fixed coil, such as in large power generators producing in both cases an alternating current.

Mathematically, Faraday’s law of induction can be expressed as,

$$E = -N\frac{d\Phi}{dt} \qquad (10)$$

Where N is the number of turns of the tightly wound coil subjected to the magnetic field (Φ).

Faraday's law is a single equation describing two different phenomena:

1) The motional EMF generated by a magnetic force on a moving wire, and
2) The transformer EMF generated by an electric force due to a time-varying magnetic field.

Lenz’s Law of Electromagnetic Induction

Faraday’s Law tells us that inducing a voltage into a conductor can be done by either passing it through a magnetic field, or by moving the magnetic field past the conductor and that if this conductor is part of a closed circuit, an electric current will flow. This voltage is called an induced emf as it has been induced into the conductor by a changing magnetic field due to electromagnetic induction with the negative sign in Faraday’s law telling us the direction of the induced current (or polarity of the induced emf).

But a changing magnetic flux produces a varying current through the coil which itself will produce its own magnetic field. This self-induced emf opposes the change that is causing it and the faster the rate of change of current the greater is the opposing emf. This self-induced emf will, by Lenz's law oppose the change in current in the coil and because of its direction this self-induced emf is generally called a back-emf.

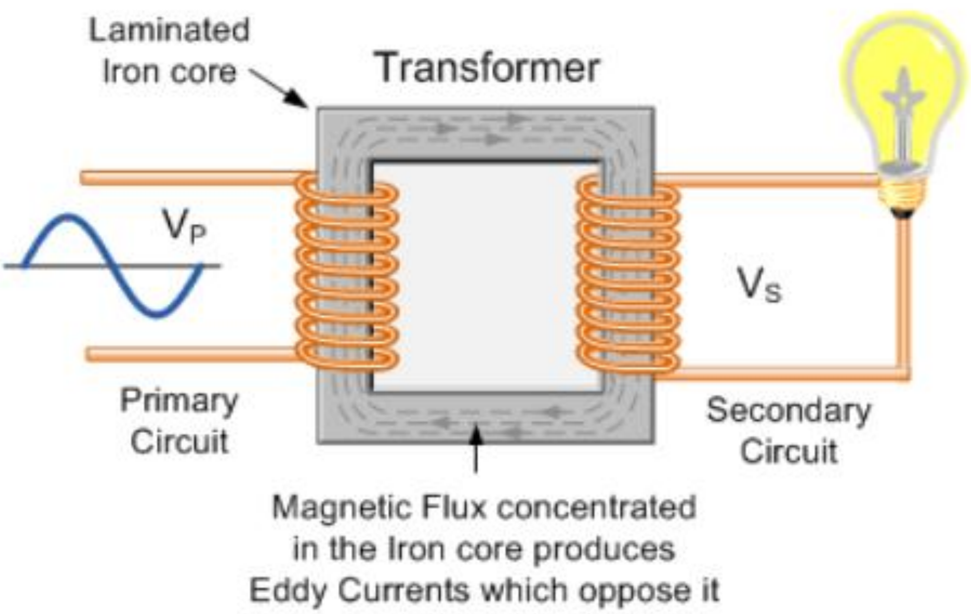
Lenz's Law states that: " *the direction of an induced emf is such that it will always opposes the change that is causing it*". In other words, an induced current will always OPPOSE the motion or change which started the induced current in the first place and this idea is found in the analysis of Inductance. Likewise, if the magnetic flux is decreased then the induced emf will oppose this decrease by generating and induced magnetic flux that adds to the original flux. Lenz's law is one of the basic laws in electromagnetic induction for determining the direction of flow of induced currents and is related to the law of conservation of energy.

According to the law of conservation of energy which states that the *total amount of energy in the universe will always remain constant as energy cannot be created nor destroyed*. Lenz's law is derived from Michael Faraday's law of induction.

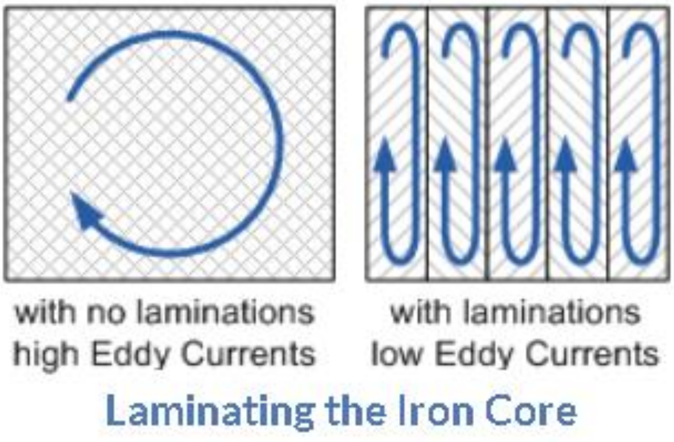
One final comment about Lenz's Law regarding electromagnetic induction; we now know that when a relative motion exists between a conductor and a magnetic field, an emf is induced within the conductor; however, the conductor may not actually be part of the coils electrical circuit, but may be the coils iron core or some other metallic part of the system, for example, a transformer. The induced emf within this metallic part of the system causes a circulating current to flow around it and this type of core current is known as an ***eddy current***.

Eddy currents generated by electromagnetic induction circulate around the coils core or any connecting metallic components inside the magnetic field because for the magnetic flux they are acting like a single loop of wire. Eddy currents do not contribute anything towards the usefulness of the system, but instead they oppose the flow of the induced current by acting like a negative force generating resistive heating and power loss within the core. However, there are electromagnetic induction furnace applications in which only eddy currents are used to heat and melt ferromagnetic metals.

Eddy Currents Circulating in a Transformer



(a)



(b)

Fig. 21: Eddy currents in a transformer core. (a) Flow of eddy current; (b) Core laminations

The changing magnetic flux in the iron core of a transformer above will induce an emf, not only in the primary and secondary windings, but also in the iron core. The iron core is a good conductor, so the currents induced in a solid iron core will be large. Furthermore, the eddy currents flow in a direction which, by Lenz's law, acts to weaken the flux created by the primary coil (Fig. 21(a)). Consequently, the current in the primary coil required to produce a given B field is increased, so the hysteresis curves are fatter along the H axis.

Eddy current and hysteresis losses cannot be eliminated completely, but they can be greatly reduced. Instead of having a solid iron core as the magnetic core material of the transformer or coil, the magnetic path is "laminated" (Fig. 21(b)). These laminations are very thin strips of insulated (usually with varnish) metal joined together to produce a solid core. The laminations increase the resistance of the iron-core thereby increasing the overall resistance to the flow of the eddy currents, so the induced eddy current power-loss in the core is reduced, and it is for this reason why the magnetic iron circuit of transformers and electrical machines are all laminated.

The next chapters will provide details about the operation concepts and performance characteristics of various types of transformers used in power, sensing, and control application.

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Chapter 2

Power Transformers

Objectives

By the end of this chapter, the following points will be covered.

- Construction layouts of transformers,
- Basics of transformers operation,
- Transformer performance characteristics, and
- Multi-winding transformers.

Construction

Generally, *a transformer is a static device that uses the phenomena of electromagnetism and electromagnetic induction for changing the values of AC voltages and AC currents while keeping the frequency unchanged. In fact, one of the main advantages of AC transmission and distribution is the ease with which AC voltages can be increased or decreased by transformers.*

Transformers range in size from the miniature units of several watts rating used in electronic applications to the large power transformers of several MWs used in power stations; the principle of operation is the same for each; however, miniature transformers are usually single-phase of either two windings or several windings. Larger ratings of power transformers used in power systems are usually of three-phase types.

As shown in Fig. 1, a simple two-winding transformer construction. The transformer is consists of two electrical circuits (also called windings, or coils) linked by a common ***ferromagnetic core***. One coil is termed the ***primary winding*** which is connected to the supply of electricity, and the other the ***secondary winding***, which may be connected to a load. The construction consists of each winding being wound on a separate soft iron limb or core which provides the necessary magnetic circuit. This magnetic circuit, know more commonly as the "transformer core" is designed to provide a path for the magnetic field to flow around, which is necessary for induction of the voltage between the two windings. This type of transformer construction where the two windings are wound on separate limbs is not very efficient since the primary and secondary windings are well separated from each other. This results in a low magnetic coupling between the two windings as well as large amounts of magnetic flux leakage from the transformer itself. But as well as this "O" shapes construction, there are different types of "transformer construction" and designs available which are used to overcome these inefficiencies producing a smaller more compact transformer.

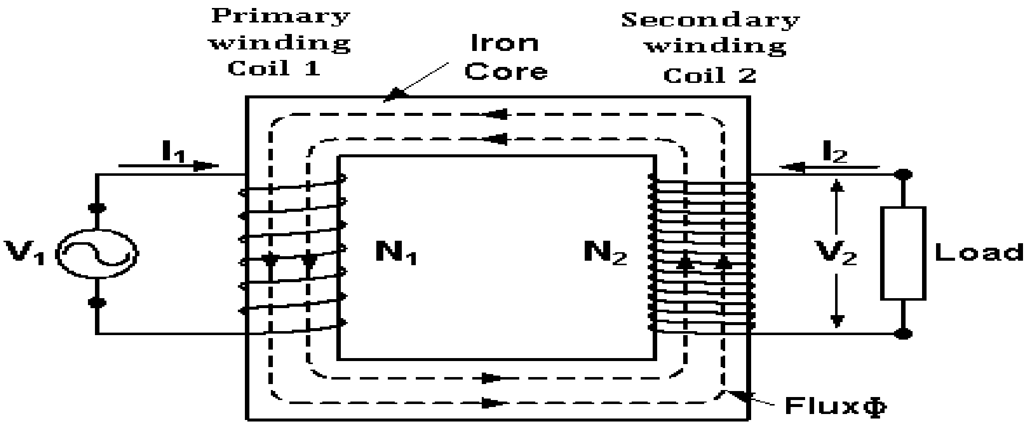


Fig. 1: A simple two-winding single-phase transformer

It can also be seen from Fig. 1 that *transformers not only enable current or voltage to be transformed to some different magnitude, but they provide a means of electrically isolating one part of a circuit (i.e. the primary circuit) from another part (i.e. the secondary side) through the magnetic coupling between these electrical windings.*

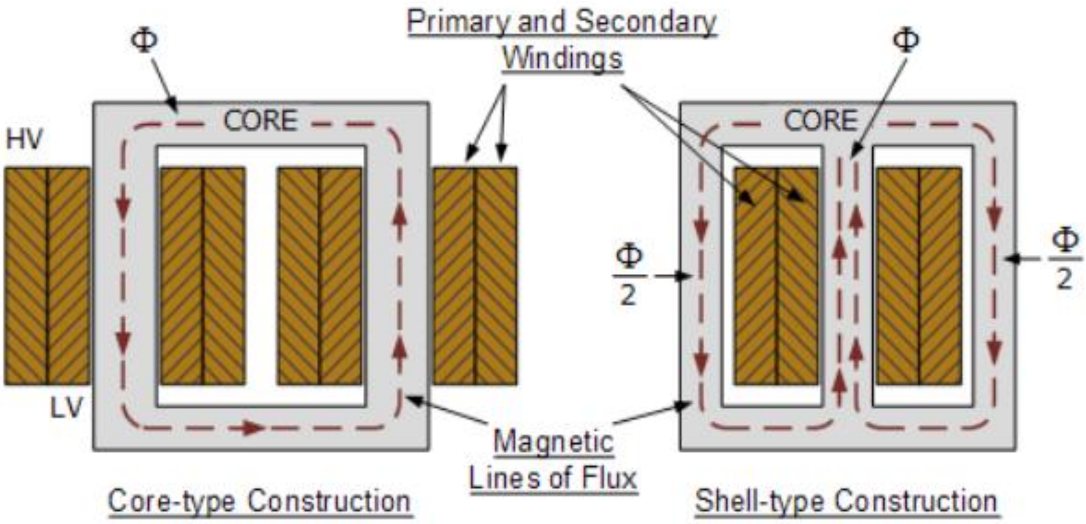
The efficiency of a simple transformer construction can be improved by bringing the two windings within close non-electrical contact with each other thereby improving the magnetic coupling and reducing the leakage flux. Increasing and concentrating the magnetic circuit around the coils may improve the magnetic coupling between the two windings, but it also has the effect of increasing the magnetic losses of the transformer core as the flux density increases (see the previous chapter). Consequently, the risks of reaching the magnetic saturation level are higher.

As well as providing a low reluctance path for the magnetic field, the core is usually designed for preventing circulating electric currents within the iron core itself. Circulating currents, called "eddy currents" as described in the previous chapter, cause heating and energy losses within the core decreasing the transformers efficiency. These losses are mainly due to voltages induced in the iron circuit, which is constantly being subjected to the alternating magnetic fields setup by the external sinusoidal supply voltage. One way to reduce these unwanted power losses is to construct the transformer core from thin steel laminations as briefly illustrated in the previous chapter.

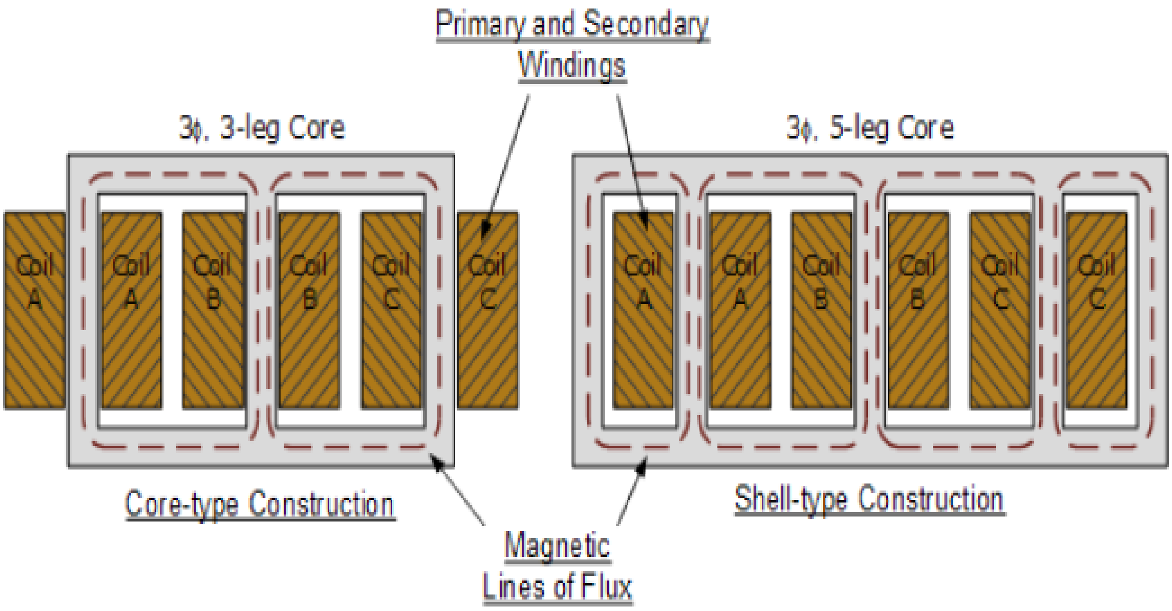
In all types of transformer construction, the central iron core is constructed from of a highly permeable material made from thin silicon steel laminations. These thin laminations are assembled together to provide the required magnetic path with the minimum of magnetic losses. The resistivity of the steel sheet itself is high, thus reducing any eddy current loss by making the laminations very thin. These steel transformer laminations vary in thickness's from between 0.25 mm to 0.5 mm and as steel is a conductor, the laminations and any fixing studs, rivets or bolts are electrically insulated from each other by a very thin coating of insulating varnish or by the use of an oxide layer on the surface.

Transformer Core

Generally, the name associated with the construction type of a transformer is dependent upon how the primary and secondary windings are wound around the central laminated steel core. The two most common and basic designs of transformer construction are the ***closed-core Transformer*** (also called ***core-type transformer***), and the ***shell-core transformer*** (also called ***shell-type transformer***); see Fig. 2.



(a)



(b)

Fig. 2: Main constructions. (a) Single-phase power transformers; (b) Three-phase power transformer

In the "closed-core" type (core form) transformer, the primary and secondary windings are wound outside and surround the core ring. In the "shell type" (shell form) transformer, the primary and secondary windings pass inside the steel magnetic circuit (core) which forms a shell around the windings as shown in Fig. 2. In both types of transformer core design, the magnetic flux linking the primary and secondary windings travels entirely within the core with no loss of magnetic flux through air.

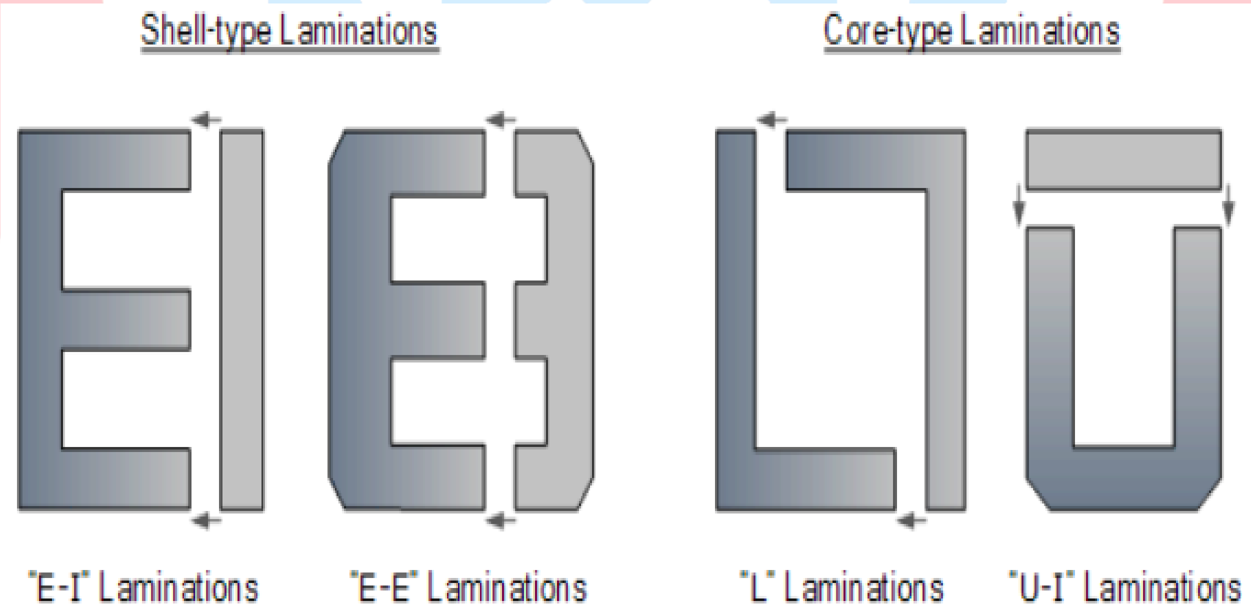
In the core type transformer construction, one half of each winding is wrapped around each leg (or limb) of the transformers magnetic circuit as shown above. The coils are not arranged with the primary winding on one leg and the secondary on the other but instead half of the primary winding and half of the secondary winding are placed one over the other concentrically on each leg in order to increase magnetic coupling allowing practically all of the magnetic lines of force go through both the primary and secondary windings at the same time. However, with this type of transformer construction, a small percentage of the magnetic lines of force flow outside of the core, and this is called "leakage flux".

Shell type transformer cores overcome this leakage flux as both the primary and secondary windings are wound on the same centre leg or limb which has twice the cross-sectional area of the two outer limbs. The advantage here is that the magnetic flux has two closed magnetic paths to flow around external to the coils on both left and right hand sides before returning back to the central coils. This means that the magnetic flux circulating around the outer limbs of this type of transformer construction is equal to $\Phi/2$. As the magnetic flux has a closed path around the coils, this has the advantage of decreasing core losses and increasing overall efficiency.

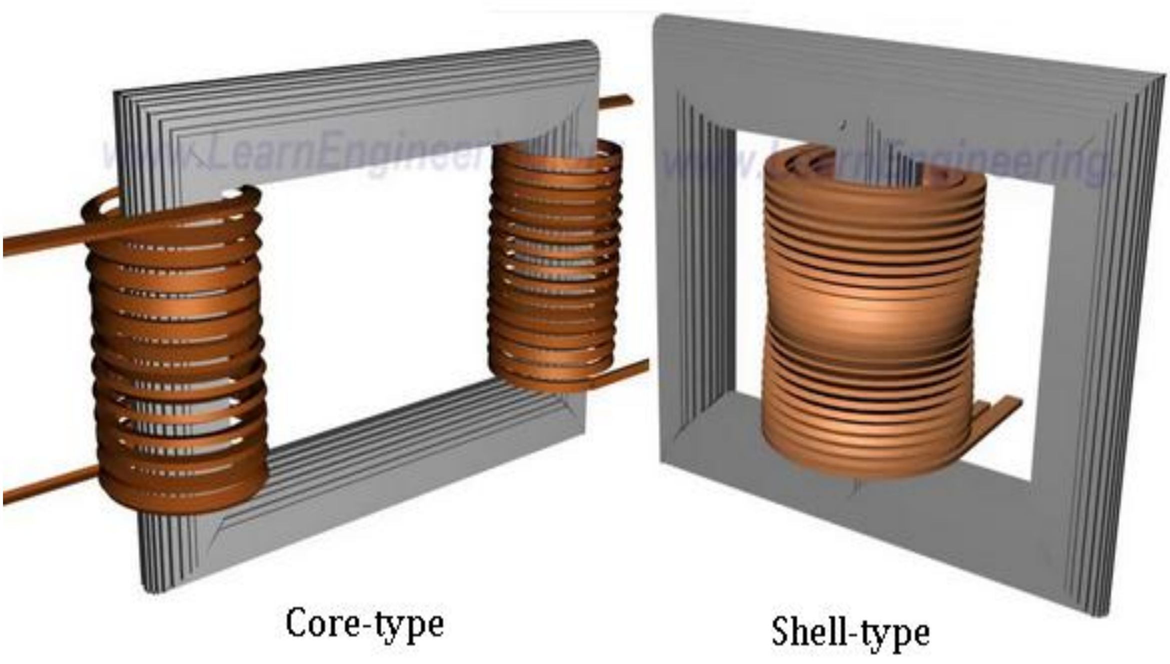
It is worthy to note that the core-type and shell-type three phase power transformer constructions follow the same concepts of the single-phase transformers; see Fig. 2

But you may be wondering as to how the primary and secondary windings are wound around these laminated iron or steel cores for these types of transformer constructions. The coils are firstly wound on a former which has a cylindrical, rectangular or oval type cross section to suit the construction of the laminated core. In both the shell and core type transformer constructions, in order to mount the coil windings, the individual laminations are stamped or punched out from larger steel sheets and formed into strips of thin steel resembling the letters "E"s, "L"s, "U"s and "I"s as shown Fig. 3.

These lamination stampings when connected together form the required core shape. For example, two "E" stampings plus two end closing "I" stampings to give an E-I core forming one element of a standard shell-type transformer core. These individual laminations are tightly butted together during the transformers construction to reduce the reluctance of the air gap at the joints producing a highly saturated magnetic flux density. Transformer core laminations are usually stacked alternately to each other to produce an overlapping joint with more lamination pairs being added to make up the correct core thickness. This alternate stacking of the laminations also gives the transformer the advantage of reduced flux leakage and iron losses. E-I core laminated transformer construction is mostly used in isolation transformers, step-up and step-down transformers as well as auto transformers.



(a)



(b)

Fig. 3: Single-phase transformers. (a) Core laminations; (b) Assembly

Transformer Windings

Transformer windings form another important part of a transformer construction, because they are the main current-carrying conductors wound around the laminated sections of the core. In a single-phase two winding transformer, two windings would be present as shown in Fig. 1 and Fig. 3. The one which is connected to the voltage source and creates the magnetic flux called the primary winding, and the second winding called the secondary in which a voltage is induced as a result of mutual induction. Three-phase transformers follow the same principles as shown in Fig. 4 for a core-type three-phase transformer.

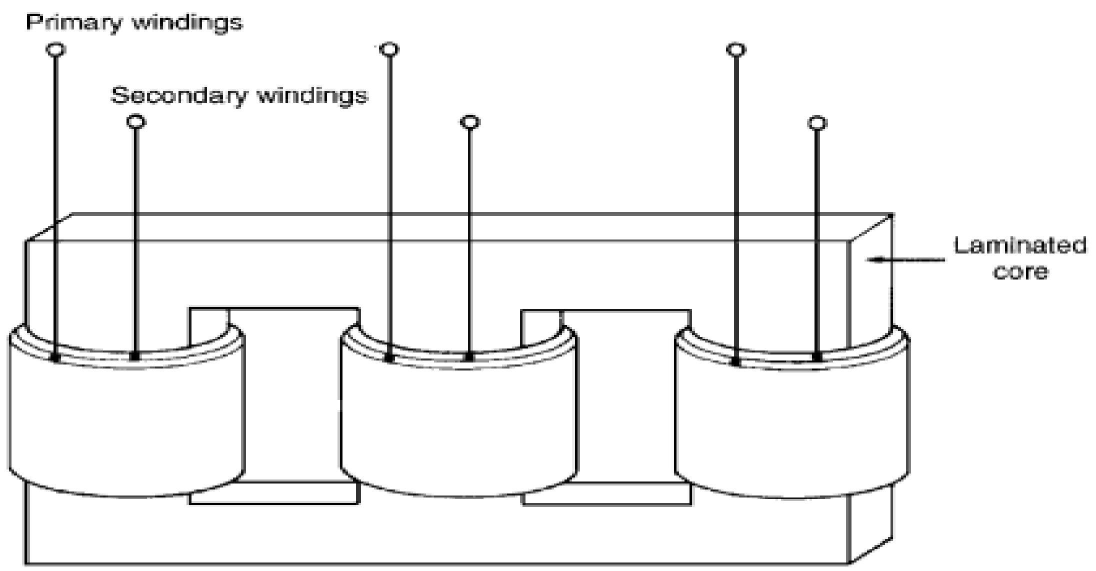
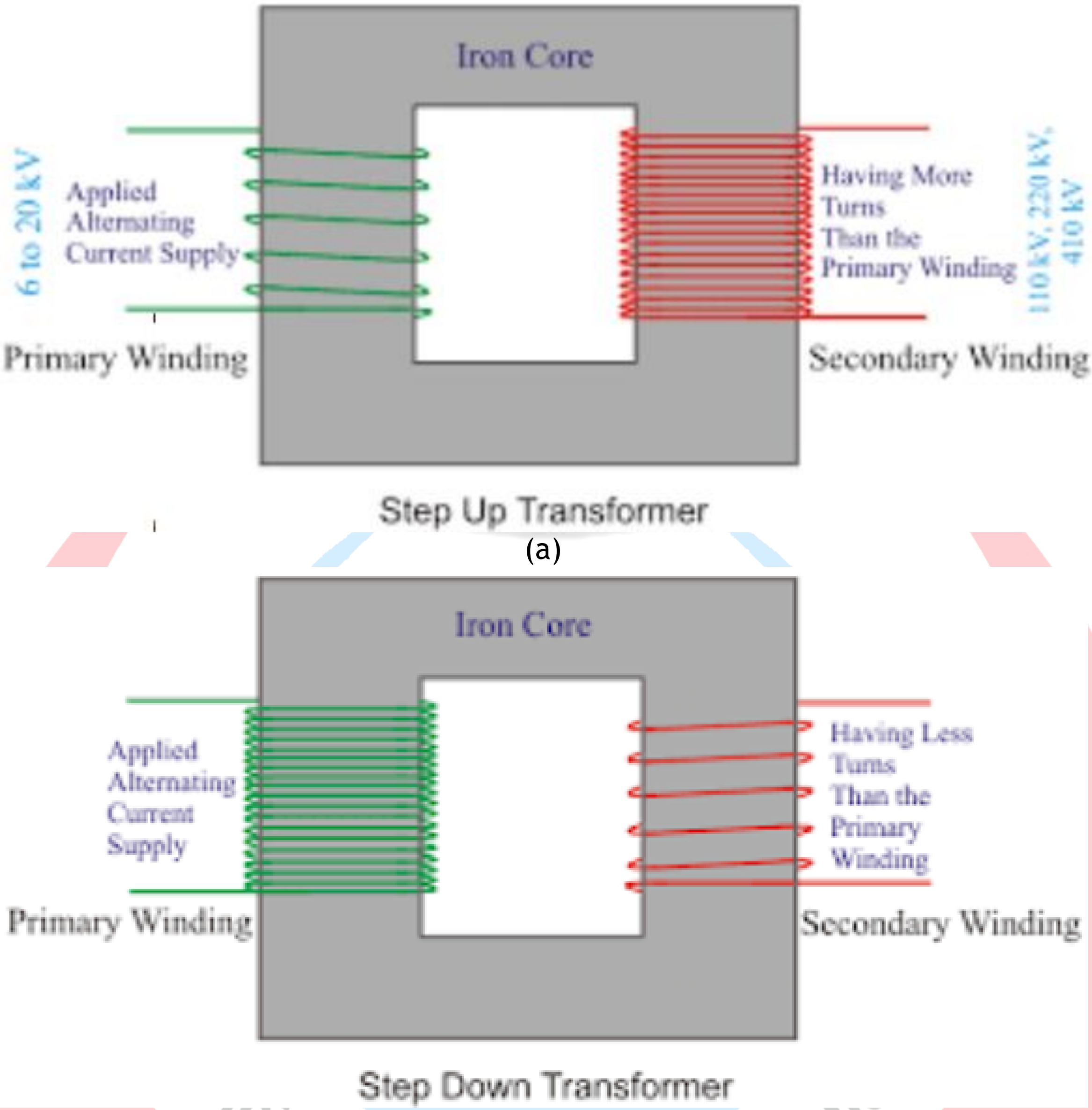


Fig. 4: Core-type three-phase transformer

If the secondary output voltage is less than that of the primary input voltage the transformer is known as a "***Step-down Transformer***". If the secondary output voltage is greater, then the primary input voltage it is called a "***Step-up Transformer***". See Fig. 5. As shown, in the step-up transformers, the number of turns in the primary winding is lower than the number of turns of its secondary winding. On the other hand, the number of turns of the primary winding of a step-down transformer is higher than the number of turns of its secondary winding.

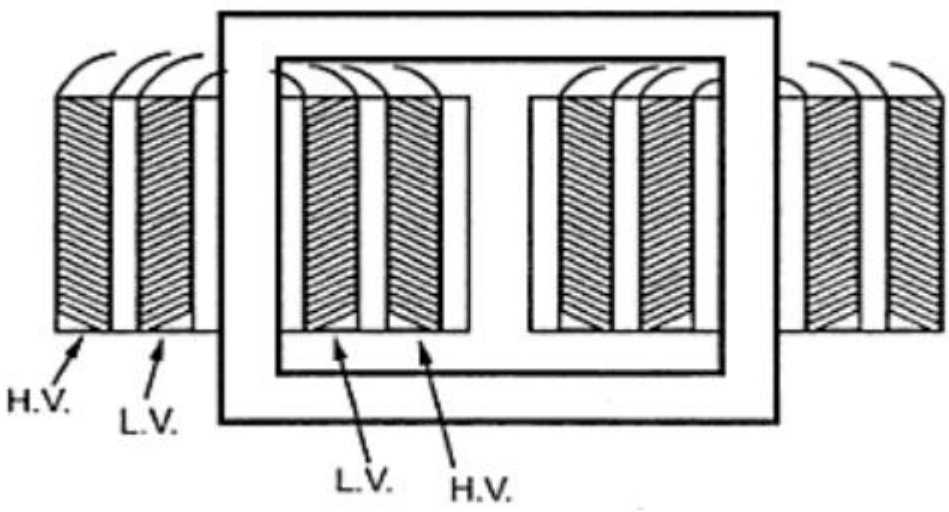


(b)

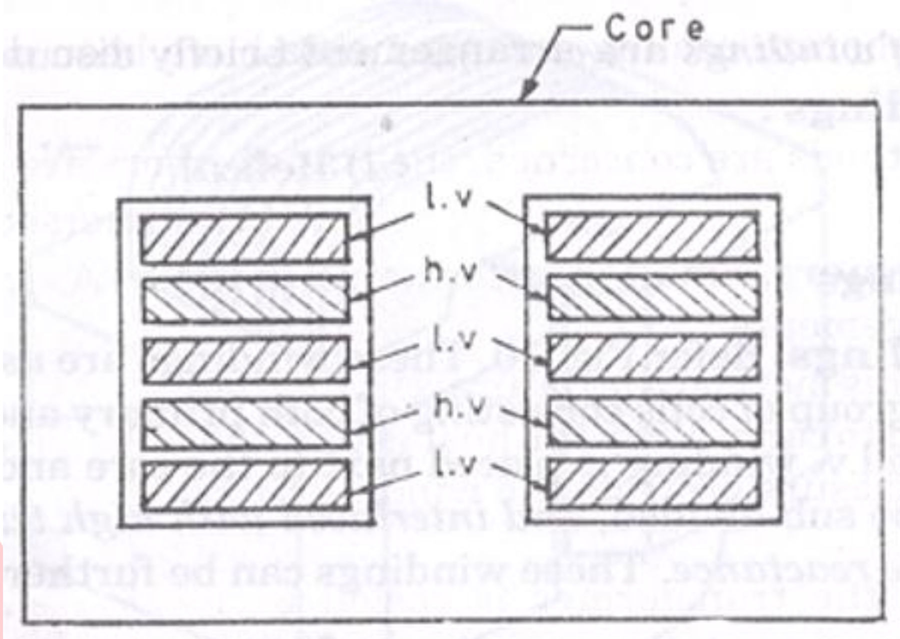
Fig. 5: Relative number of turns in step-up and step-down transformers

The type of wire used as the main current carrying conductor in a transformer winding is either copper or aluminum. While aluminum wire is lighter and generally less expensive than copper wire, a larger cross sectional area of conductor must be used to carry the same amount of current as with copper so it is used mainly in larger power transformer applications. Small kVA power and voltage transformers used in low voltage electrical and electronic circuits tend to use copper conductors as these have a higher mechanical strength and smaller conductor size than their equivalent aluminum types. The downside is that when complete with their core, these transformers are much heavier.

Transformer windings and coils can be broadly classified in to ***concentric coils*** and ***sandwiched coils*** as shown in Fig. 6. In core-type transformer construction, the windings are usually arranged concentrically around the core limb as shown in Fig. 2 with the higher voltage primary winding being wound over the lower voltage secondary winding. ***Sandwiched*** or "***pancake***" coils consist of flat conductors wound in a spiral form and are so named due to the arrangement of conductors into discs. Alternate discs are made to spiral from outside towards the centre in an interleaved arrangement with individual coils being stacked together and separated by ***insulating materials*** such as paper of plastic sheet. Sandwich coils and windings are more common with shell type core construction.



(a)



(b)

Fig. 6: Transformer coils; (a) Concentric coils; (b) Sandwich coils

Helical Windings also known as ***screw windings*** are another very common cylindrical coil arrangement used in low voltage high current transformer applications. The windings are made up of large cross sectional rectangular conductors wound on its side with the insulated strands wound in parallel continuously along the length of the cylinder, with suitable spacers inserted between adjacent turns or discs to minimize circulating currents between the parallel strands; see Fig. 7. The coil progresses outwards as a helix resembling that of a corkscrew. The insulation used to prevent the conductors shorting together in a transformer is usually a thin layer of varnish or enamel in air cooled transformers (the cooling will be described at the end of this chapter). This thin varnish or enamel paint is painted onto the wire before it is wound around the core. In larger power and distribution transformers the conductors are insulated from each other using oil impregnated paper or cloth. The whole core and windings is immersed and sealed in a protective tank containing transformer oil. The transformer oil acts as an insulator and also as a coolant.

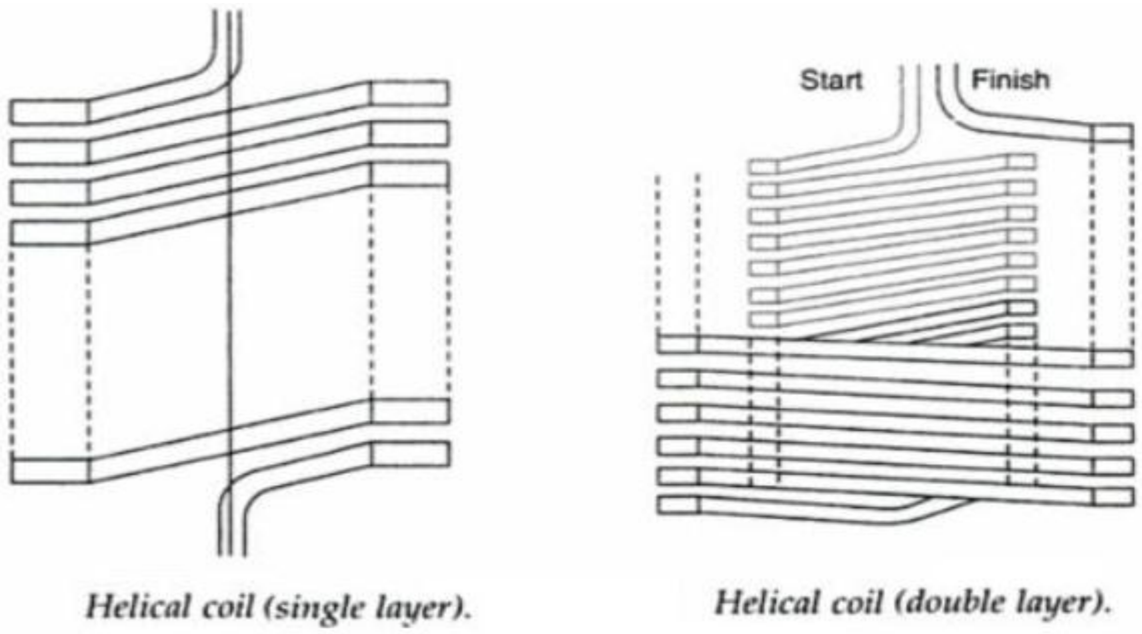


Fig. 7: Helical windings

Dot Orientation

We cannot just simply take a laminated core and wrap one of the coil configurations around it. We could but we may find that the secondary voltage and current may be out-of-phase with that of the primary voltage and current; see Fig. 8. The two coil windings do have a distinct orientation of one with respect to the other. Either coil could be wound around the core clockwise or anticlockwise so to keep track of their relative orientations "dots" are used to identify a given end of each winding.

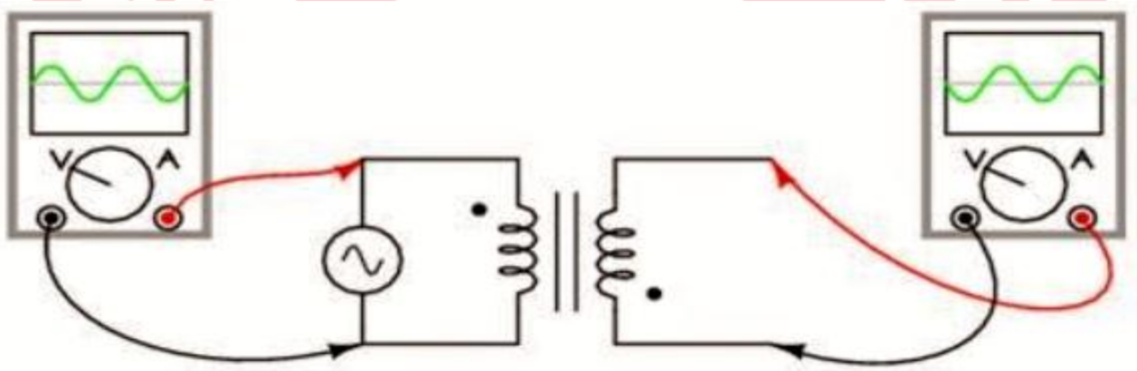
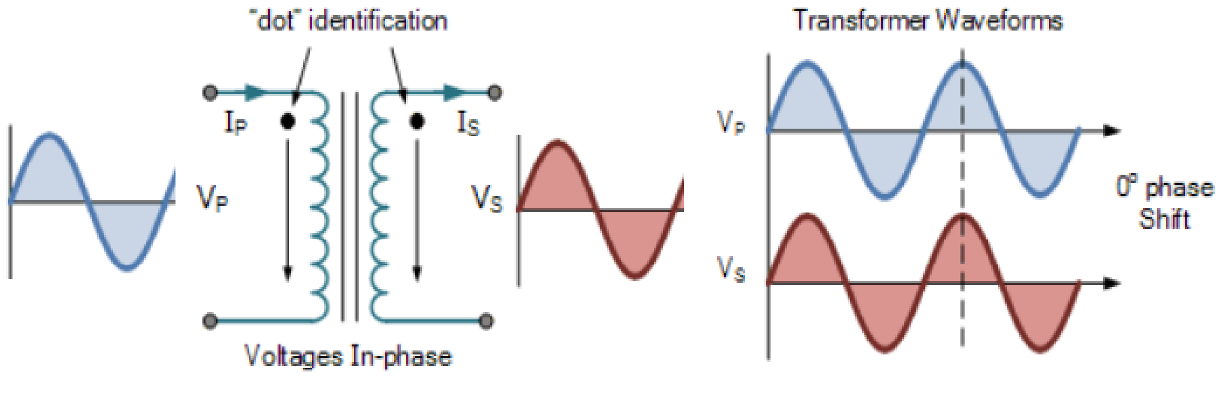
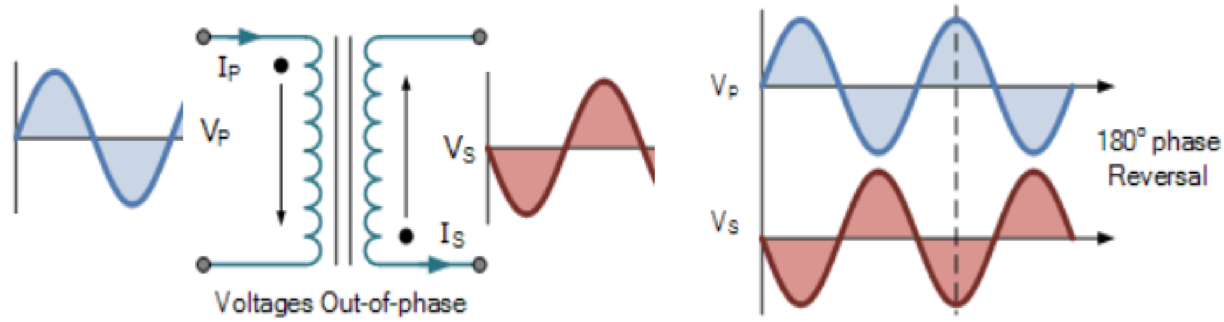


Fig. 8: Phasing dot of transformer windings



(a) In-phase connection



(b) Out-of-phase connection

Fig. 9: Use of phasing dots for correct operation of transformers

This method of identifying the orientation or direction of a transformers windings is called the "dot convention". Then transformers windings are wound so that the correct phase relations exist between the winding voltages with the transformers polarity being defined as the relative polarity of the secondary voltage with respect to the primary voltage as shown below.

For example, consider the two transformers shown in Fig. 9. The first transformer (Fig. 9(a)) shows its two "dots" side by side on the two windings. The current leaving the secondary dot is "in-phase" with the current entering the primary side dot. Thus the polarities of the voltages at the dotted ends are also in-phase so when the voltage is positive at the dotted end of the primary coil, the voltage across the secondary coil is also positive at the dotted end. The second transformer (Fig. 9(b)) shows the two dots at opposite ends of the windings which means that the transformers primary and secondary coil windings are wound in opposite directions. The result of this is that the current leaving the secondary dot is 180o "out-of-phase" with the current entering the primary dot. So the polarities of the voltages at the dotted ends are also out-of-phase so when the voltage is positive at the dotted end of the primary coil, the voltage across the corresponding secondary coil will be negative.

The construction of a transformer can be such that the secondary voltage may be either "in-phase" or "out-of-phase" with respect to the primary voltage. In transformers which have a number of different secondary windings, each of which is electrically isolated from each other it is important to know the dot polarity of the secondary windings so that they can be connected together in series-aiding (secondary voltage is summed) or series-opposing (the secondary voltage is the difference) configurations.

Tap changers

The ability to adjust the turns ratio of a transformer is often desirable to compensate for the effects of variations in the primary supply voltage, the regulation of the transformer or varying load conditions. Voltage control of the transformer is generally performed by changing the turns ratio and therefore its voltage ratio whereby a part of the primary winding on the high voltage side is tapped out allowing for easy adjustment. The tapping is preferred on the high voltage side as the volts per turn are lower than the low voltage secondary side.

For example, consider the primary tap changer shown Fig. 10. In this simple example, the primary tap changes are calculated for a supply voltage change of ±5%, but any value can be chosen. Some transformers may have two or more primary or two or more secondary windings for use in different applications providing different voltages from a single core.

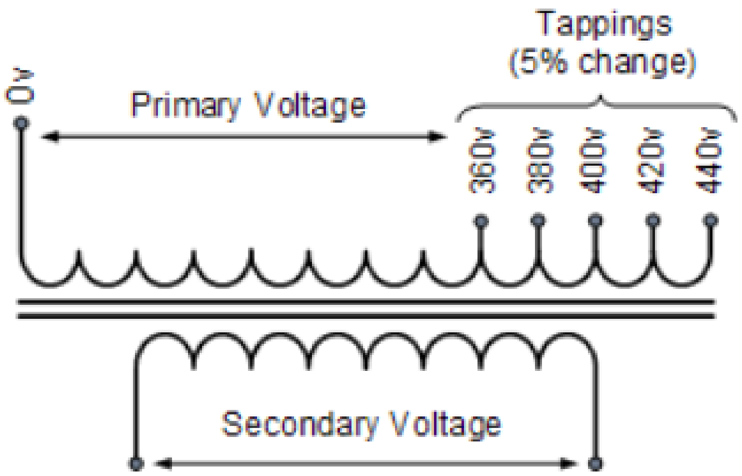


Fig. 10: Primary tap changer

Transformer Losses

There are many sources of losses in transformers, but they can be generally classified into core losses, and winding losses. The former includes the hysteresis losses and the eddy current losses, while the later include the losses of the winding material which is usually copper.

Core losses

The ability of iron or steel to carry magnetic flux is much greater than it is in air, and this ability to allow magnetic flux to flow is called permeability. Most transformer cores are constructed from low carbon steels which can have permeabilities in the order of 1500 compared with just 1.0 for air. This means that a steel laminated core can carry a magnetic flux 1500 times better than that of air. However, when a magnetic flux flows in a transformers steel core, two types of losses occur in the steel. One termed “eddy current losses” and the other termed “hysteresis losses”.

Hysteresis Losses. Transformer Hysteresis Losses are caused because of the friction of the molecules against the flow of the magnetic lines of force required to magnetize the core, which are constantly changing in value and direction first in one direction and then the other due to the influence of the sinusoidal supply voltage. This molecular friction causes heat to be developed which represents an energy loss to the transformer. Excessive heat loss can overtime shorten the life of the insulating materials used in the manufacture of the windings and structures. Therefore, cooling of a transformer is important. Also, transformers are designed to operate at a particular supply frequency. Lowering the frequency of the supply will result in increased hysteresis and higher temperature in the iron core. So reducing the supply frequency from 60 Hertz to 50 Hertz will raise the amount of hysteresis present, decreased the VA capacity of the transformer.

Eddy Current Losses. Transformer Eddy Current Losses on the other hand are caused by the flow of circulating currents induced into the steel caused by the flow of the magnetic flux around the core. These circulating currents are generated because to the magnetic flux the core is acting like a single loop of wire. Since the iron core is a good conductor, the eddy currents induced by a solid iron core will be large. Eddy currents do not contribute anything towards the usefulness of the transformer but instead they oppose the flow of the induced current by acting like a negative force generating resistive heating and power loss within the core. Eddy current losses within a transformer core cannot be eliminated completely, but they can be greatly reduced and controlled by reducing the thickness of the steel core. Instead of having one big solid iron core as the magnetic core material of the transformer or coil, the magnetic path is split up into many thin pressed steel shapes called “laminations”. The laminations used in a transformer construction are very thin strips of insulated metal joined together to produce a solid but laminated core as we saw above. These laminations are insulated from each other by a coat of varnish or paper to increase the effective resistivity of the core thereby increasing the overall resistance to limit the flow of the eddy currents. The result of all this insulation is that the unwanted induced eddy current power-loss in the core is greatly reduced, and it is for this reason why the magnetic iron circuit of every transformer and other electromagnetic machines are all laminated. Using laminations in a transformer construction reduces eddy current losses.

The losses of energy, which appears as heat due both to hysteresis and to eddy currents in the magnetic path, is known commonly as “***transformer core losses***”. Since these losses occur in all magnetic materials as a result of alternating magnetic fields. Transformer core losses are always present in a transformer whenever the primary is energized, *even if no load is connected to the secondary winding*. Also these hysteresis and the eddy current losses are sometimes referred to as “***transformer iron losses***”, as the magnetic flux causing these losses is constant at all loads.

Winding losses

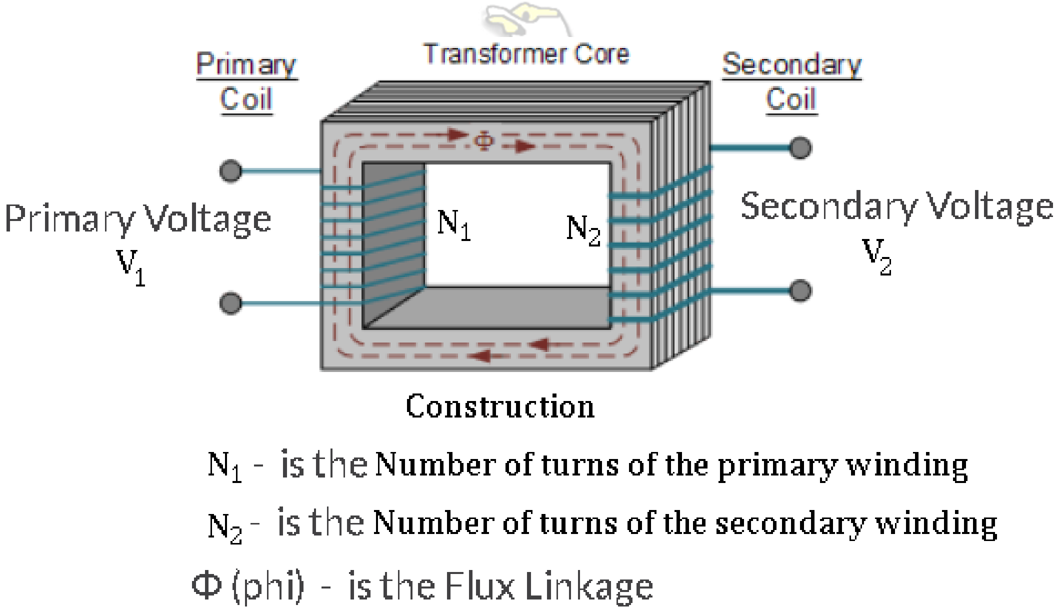
There is also another type of energy loss associated with transformers called “***winding or copper losses***”. Transformer Copper Losses are mainly due to the ***electrical resistance of the primary and secondary windings***. Most transformer coils are made from copper wire which has resistance in Ohms, (Ω). This resistance opposes the magnetizing currents flowing through them.

When a load is connected to the transformers secondary winding, large electrical currents flow in both the primary and the secondary windings, electrical energy and power (or the I^2R) losses occur as heat. Generally copper losses vary with the load current, being almost zero at no-load, and at a maximum at full-load when current flow is at maximum. A transformers VA rating can be increased by better design and transformer construction to reduce these core and copper losses. Transformers with high voltage and current ratings require conductors of large cross-section to help minimize their copper losses. Increasing the rate of heat dissipation (better cooling) by forced air or oil, or by improving the transformers insulation so that it will withstand higher temperatures can also increase a transformers VA rating. Then we can define an ideal transformer as having:

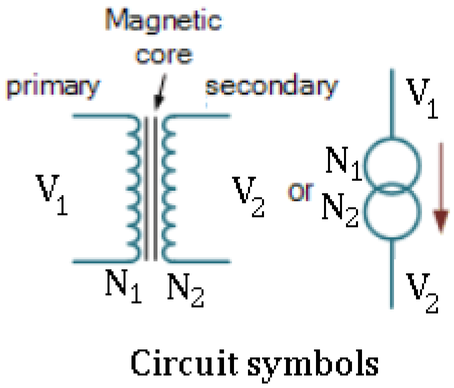
- ✓ No Hysteresis loops or Hysteresis losses $\rightarrow 0$
- ✓ Infinite Resistivity of core material giving zero Eddy current losses $\rightarrow 0$
- ✓ Zero winding resistance giving zero I^2R copper losses $\rightarrow 0$

Basics of Operation

One of the main reasons that we use alternating AC voltages and currents in our homes and workplace's is that AC supplies can be easily generated at a convenient voltage, transformed (hence the name transformer) into much higher voltages and then distributed around the country using a national grid of pylons and cables over very long distances.



(a)



(b)

Fig. 11: Single-phase transformer with various quantities defined

The reason for transforming the voltage to a much higher level is that higher distribution voltages implies lower currents for the same power and therefore lower I^2R losses along the networked grid of cables. These higher AC transmission voltages and currents can then be reduced to a much lower, safer and usable voltage level where it can be used to supply electrical equipment in our homes and workplaces, and all this is possible thanks to the basic Voltage Transformer.

Consider the single-phase transformer shown in Fig. 11. Notice that the two coil windings are not electrically connected but are only linked magnetically. A single-phase transformer can operate to either increase or decrease the voltage applied to the primary winding. When a transformer is used to "increase" the voltage on its secondary winding with respect to the primary, it is called a Step-up transformer. When it is used to "decrease" the voltage on the secondary winding with respect to the primary it is called a Step-down transformer; however, a third condition exists in which a transformer produces the same voltage on its secondary as is applied to its primary winding. In other words, its output is identical with respect to voltage, current and power transferred. This type of transformer is called an "Impedance Transformer" and is mainly used for impedance matching or the isolation of adjoining electrical circuits.

The difference in voltage between the primary and the secondary windings is achieved by changing the number of coil turns in the primary winding (N_1) compared to the number of coil turns on the secondary winding (N_2). As the transformer is basically a linear device, a ratio now exists between the number of turns of the primary coil divided by the number of turns of the secondary coil. This ratio, called the ratio of transformation, more commonly known as a transformers "turns ratio", (TR). This turns ratio value dictates the operation of the transformer and the corresponding voltage available on the secondary winding.

It is necessary to know the ratio of the number of turns of wire on the primary winding compared to the secondary winding. The turns ratio, which has no units, compares the two windings in order and is written with a colon, such as 3:1 (3-to-1). This means in this example, that if there are 3 volts on the primary winding there will be 1 volt on the secondary winding, 3 volts-to-1 volt. Then we can see that if the ratio between the number of turns changes the resulting voltages must also change by the same ratio, and this is true.

Transformers are all about "ratios". The ratio of the primary to the secondary, the ratio of the input to the output, and the turns ratio of any given transformer will be the same as its voltage ratio. In other words for a transformer: "turns ratio = voltage ratio". ***The actual number of turns of wire on any winding is generally not important, just the turns ratio: TR = N_1/N_2***. The following relations are applicable.

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} \quad (1)$$

This relation indicates that the ***voltage per turn***, and the ***ampere-turn*** are constants provided that the flux leakage is neglected i.e. $\Phi_1 = \Phi_2$ which indicate an ideality assumption.

Example 1

A transformer has 500 primary turns and 3000 secondary turns. If the primary voltage is 240 V, determine the secondary voltage, assuming an ideal transformer.

Solution

For an ideal transformer, voltage ratio = turns ratio i.e.

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \text{ hence } \frac{240}{V_2} = \frac{500}{3000}$$

Thus secondary voltage

$$V_2 = \frac{(240)(3000)}{500} = \mathbf{1440\,V \text{ or } 1.44\,kV}$$

Example 2

An ideal transformer with a turns ratio of 2:7 is fed from a 240 V supply. Determine its output voltage.

Solution

A turns ratio of 2:7 means that the transformer has 2 turns on the primary for every 7 turns on the secondary (i.e. a step-up transformer); thus $(N_1/N_2) = (2/7)$.

For an ideal transformer, $(N_1/N_2) = (V_1/V_2)$ hence $(2/7) = (240/V_2)$ Thus the secondary voltage

$$\mathbf{V_2} = \frac{(240)(7)}{2} = \mathbf{840\ V}$$

Example 3

An ideal transformer has a turns ratio of 8:1 and the primary current is 3 A when it is supplied at 240 V. Calculate the secondary voltage and current.

Solution

A turns ratio of 8:1 means $(N_1/N_2) = (1/8)$ i.e. a step-down transformer.

$$\left(\frac{N_1}{N_2}\right) = \left(\frac{V_1}{V_2}\right) \text{ or secondary voltage}$$

$$\mathbf{V_2} = V_1\left(\frac{N_1}{N_2}\right) = 240\left(\frac{1}{8}\right) = \mathbf{30\ volts}$$

Also, $\left(\frac{N_1}{N_2}\right) = \left(\frac{I_2}{I_1}\right)$ hence secondary current

$$\mathbf{I_2} = I_1\left(\frac{N_1}{N_2}\right) = 3\left(\frac{8}{1}\right) = \mathbf{24\ A}$$

Example 4

An ideal transformer, connected to a 240 V mains, supplies a 12 V, 150 W lamp. Calculate the transformer turns ratio and the current taken from the supply.

Solution

$V_1 = 240\,\text{V},\ V_2 = 12\,\text{V},\ I_2 = (P/V_2) = (150/12) = 12.5\,\text{A}.$

$$\textbf{Turns ratio} = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{240}{12} = \mathbf{20}$$

$$\left(\frac{V_1}{V_2}\right) = \left(\frac{I_2}{I_1}\right), \text{ from which,}$$

$$I_1 = I_2\left(\frac{V_2}{V_1}\right) = 12.5\left(\frac{12}{240}\right)$$

Hence current taken from the supply,

$$\boldsymbol{I_1} = \frac{12.5}{20} = \mathbf{0.625\,A}$$

Example 5

A 12 Ω resistor is connected across the secondary winding of an ideal transformer whose secondary voltage is 120 V. Determine the primary voltage if the supply current is 4 A.

Solution

Secondary current $I_2 = (V_2/R_2) = (120/12) = 10\,\text{A}.$

$(V_1/V_2) = (I_2/I_1)$, from which the primary voltage

$$\boldsymbol{V_1} = V_2\left(\frac{I_2}{I_1}\right) = 120\left(\frac{10}{4}\right) = \mathbf{300\ volts}$$

Example 6

A 5 kVA single-phase transformer has a turns ratio of 10 : 1 and is fed from a 2.5 kV supply. Neglecting losses, determine

a) The full-load secondary current,
b) The minimum load resistance which can be connected across the secondary winding to give full load kVA,
c) The primary current at full load kVA.

Solution

(a) $N_1/N_2 = 10/1$ and $V_1 = 2.5\,\text{kV} = 2500\,\text{V}$.

Since $\left(\frac{N_1}{N_2}\right) = \left(\frac{V_1}{V_2}\right)$, secondary voltage

$$V_2 = V_1\left(\frac{N_2}{N_1}\right) = 2500\left(\frac{1}{10}\right) = 250\,\text{V}$$

The transformer rating in volt-amperes $= V_2 I_2$ (at full load) i.e. $5000 = 250 I_2$

Hence full load secondary current $I_2 = (5000/250) = \mathbf{20\,A}$.

(b) Minimum value of load resistance,

$$R_L = \left(\frac{V_2}{V_1}\right) = \left(\frac{250}{20}\right) = \mathbf{12.5\,\Omega}.$$

(c) $\left(\frac{N_1}{N_2}\right) = \left(\frac{I_2}{I_1}\right)$ from which primary current

$$I_1 = I_2\left(\frac{N_1}{N_2}\right) = 20\left(\frac{1}{10}\right) = \mathbf{2\,A}$$

Problems

1. A transformer has 600 primary turns connected to a 1.5 kV supply. Determine the number of secondary turns for a 240 V output voltage, assuming no losses. [96]
2. An ideal transformer with a turns ratio of 2:9 is fed from a 220 V supply. Determine its output voltage. [990 V]
3. A transformer has 800 primary turns and 2000 secondary turns. If the primary voltage is 160 V, determine the secondary voltage assuming an ideal transformer. [400 V]
4. An ideal transformer with a turns ratio of 3:8 is fed from a 240 V supply. Determine its output voltage. [640 V]
5. An ideal transformer has a turns ratio of 12:1 and is supplied at 192 V. Calculate the secondary voltage. [16 V]
6. A transformer primary winding connected across a 415 V supply has 750 turns. Determine how many turns must be wound on the secondary side if an output of 1.66 kV is required. [3000 turns]
7. An ideal transformer has a turns ratio of 12:1 and is supplied at 180 V when the primary current is 4 A. Calculate the secondary voltage and current. [15 V, 48 A]
8. A step-down transformer having a turns ratio of 20:1 has a primary voltage of 4 kV and a load of 10 kW. Neglecting losses, calculate the value of the secondary current. [50 A]
9. A transformer has a primary to secondary turns ratio of 1:15. Calculate the primary voltage necessary to supply a 240 V load. If the load current is 3 A determine the primary current. Neglect any losses. [16 V, 45 A]
10. A 10 kVA, single-phase transformer has a turns ratio of 12:1 and is supplied from a 2.4 kV supply. Neglecting losses, determine (a) the full load secondary current, (b) the
11. minimum value of load resistance which can be connected across the secondary winding without the kVA rating being exceeded, and (c) the primary current.

Transformer Action

We have seen that the number of coil turns on the secondary winding compared to the primary winding, the turns ratio, affects the amount of voltage available from the secondary coil. But if the two windings are electrically isolated from each other, how is this secondary voltage produced?

We have said previously that a transformer basically consists of two coils wound around a common soft iron core. When an alternating voltage (V_1) is applied to the primary coil, current flows through the coil which in turn sets up a magnetic field around itself, called mutual inductance, by this current flow according to Faraday's Law of electromagnetic induction; Fig. 12. The strength of the magnetic field builds up as the current flow rises from zero to its maximum value which is given as dΦ/dt. As the magnetic lines of force setup by this electromagnet expand outward from the coil the soft iron core forms a path for and concentrates the magnetic flux. This magnetic flux links the turns of both windings as it increases and decreases in opposite directions under the influence of the AC supply. However, the strength of the magnetic field induced into the soft iron core depends upon the amount of current and the number of turns in the winding. When current is reduced, the magnetic field strength reduces.

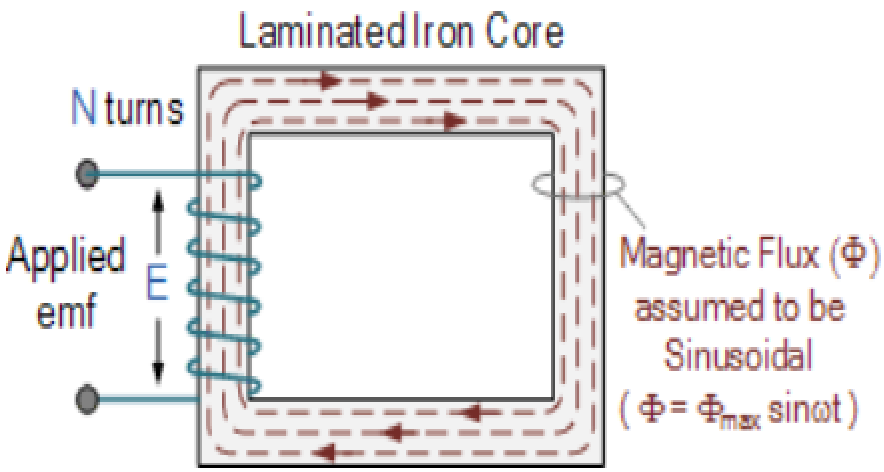


Fig. 12: Transformer action

Ahen the magnetic lines of flux flow around the core, they pass through the turns of the secondary winding, causing a voltage to be induced into the secondary coil. The amount of voltage induced will be determined by: N*dΦ/dt (Faraday's Law), where N is the number of coil turns. Also this induced voltage has the same frequency as the primary winding voltage. Then we can see that the same voltage is induced in each coil turn of both windings because the same magnetic flux links the turns of both the windings together. As a result, the total induced voltage in each winding is directly proportional to the number of turns in that winding. However, the peak amplitude of the output voltage available on the secondary winding will be reduced if the magnetic losses of the core are high.

If we want the primary coil to produce a stronger magnetic field to overcome the cores magnetic losses, we can either send a larger current through the coil, or keep the same current flowing, and instead increase the number of coil turns (N_1) of the winding. The product of amperes times turns is called the "ampere-turns", which determines the magnetizing force of the coil. So assuming we have a transformer with a single turn in the primary, and only one turn in the secondary. If one volt is applied to the one turn of the primary coil, assuming no losses, enough current must flow and enough magnetic flux generated to induce one volt in the single turn of the secondary. That is, each winding supports the same number of volts per turn.

As the magnetic flux varies sinusoidally, $\Phi = \Phi_{max} \sin\omega t$, then the basic relationship between induced emf, (E) in a coil winding of N turns is given by:

$$E_1 = 4.44 f \Phi_m N_1 \text{ volts} \quad (2)$$

$$E_2 = 4.44 f \Phi_m N_2 \text{ volts} \quad (3)$$

$$\left(\frac{E_1}{E_2}\right) = \left(\frac{N_1}{N_2}\right) \quad (4)$$

where

f - is the flux frequency in Hertz, $= \omega/2\pi$
N - is the number of coil windings.
Φ - is the amount of flux in webers

Example 7

A 100 kVA, 4000 V/200 V, 50 Hz single-phase transformer has 100 secondary turns. Determine (a) the primary and secondary current, (b) the number of primary turns, and (c) the maximum value of the flux.

Solution

$V_1 = 4000\,\text{V}$, $V_2 = 200\,\text{V}$, $f = 50\,\text{Hz}$, $N_2 = 100$ turns

(a) Transformer rating $= V_1 I_1 = V_2 I_2 = 1\,00\,000$ VA
Hence primary current,

$$I_1 = \frac{1\,00\,000}{V_1} = \frac{1\,00\,000}{4\,000} = \mathbf{25\ A}$$

and secondary current,

$$I_2 = \frac{1\,00\,000}{V_2} = \frac{1\,00\,000}{200} = \mathbf{500\ A}$$

(b) From equation (3), $\frac{V_1}{V_2} = \frac{N_1}{N_2}$ from which, primary turns,

$$N_1 = \left(\frac{V_1}{V_2}\right)(N_2) = \left(\frac{4000}{200}\right)(100) = \mathbf{2000\ turns}$$

(c) From equation (5), $E_2 = 4.44 f \Phi_m N_2$ from which, maximum flux,

$$\Phi_m = \frac{E}{4.44 f N_2}$$
$$= \frac{200}{(4.44)(50)(100)} \text{ (assuming } E_2 = V_2)$$
$$= \mathbf{9.01 \times 10^{-3} \, Wb \text{ or } 9.01 \, mWb}$$

[Alternatively, equation (4) could have been used, where

$$E_1 = 4.44 f \Phi_m N_1 \text{ from which,}$$
$$\Phi_m = \frac{4000}{(4.44)(50)(2000)} \text{ (assuming } E_1 = V_1)$$
$$= \mathbf{9.01 \, mWb \text{ as above}}]$$

Example 8

A single-phase, 50 Hz transformer has 25 primary turns and 300 secondary turns. The cross-sectional area of the core is 300 cm 2 . When the primary winding is connected to a 250 V supply, determine (a) the maximum value of the flux density in the core, and (b) the voltage induced in the secondary winding.

Solution

(a) From equation (4),
e.m.f. $E_1 = 4.44 f \Phi_m N_1$ volts
i.e. $250 = 4.44(50)\Phi_m(25)$ from which, maximum flux density,

$$\Phi_m = \frac{250}{(4.44)(50)(25)} \text{ Wb} = 0.04505 \text{ Wb}$$

However, $\Phi_m = B_m \times A$, where B_m = maximum flux density in the core and A = cross-sectional area of the core (see Chapter 7). Hence $B_m \times 300 \times 10^{-4} = 0.04505$ from which,

$$\textbf{maximum flux density, } B_m = \frac{0.04505}{300 \times 10^{-4}} = \mathbf{1.50 \, T}$$

(b) $\frac{V_1}{V_2} = \frac{N_1}{N_2}$ from which, $V_2 = V_1\left(\frac{N_2}{N_1}\right)$ i.e. voltage induced in the secondary winding,

$$V_2 = (250)\left(\frac{300}{25}\right) = \mathbf{3000 \, V \text{ or } 3 \, kV}$$

Example 9

A single-phase 500 V/100 V, 50 Hz transformer has a maximum core flux density of 1.5 T and an effective core cross-sectional area of 50 cm^2. Determine the number of primary and secondary turns.

Solution

The e.m.f. equation for a transformer is $E = 4.44 f \Phi_m N$ and maximum flux, $\Phi_m = B \times A = (1.5)(50 \times 10^{-4}) = 75 \times 10^{-4}$ Wb

Since $E_1 = 4.44 f \Phi_m N_1$ then primary turns,

$$N_1 = \frac{E_1}{4.44 f \Phi_m} = \frac{500}{(4.44)(50)(75 \times 10^{-4})}$$

$= \mathbf{300\ turns}$

Since $E_2 = 4.4 f \Phi_m N_2$ then secondary turns,

$$N_2 = \frac{E_2}{4.44 f \Phi_m} = \frac{100}{(4.44)(50)(75 \times 10^{-4})}$$

$= \mathbf{60\ turns}$

Example 10

A 4500 V/225 V, 50 Hz single-phase transformer is to have an approximate e.m.f. per turn of 15 V and operate with a maximum flux of 1.4 T. Calculate (a) the number of primary and secondary turns and (b) the cross-sectional area of the core.

Solution

(a) E.m.f. per turn $= \frac{E_1}{N_1} = \frac{E_2}{N_2} = 15$

Hence primary turns, $N_1 = \frac{E_1}{15} = \frac{4500}{15} = \mathbf{300}$

and secondary turns, $N_2 = \frac{E_2}{15} = \frac{255}{15} = \mathbf{15}$

(b) E.m.f. $E_1 = 4.44 f \Phi_m N_1$ from which,

$$\Phi_m \frac{E_1}{4.44 f N_1} = \frac{4500}{(4.44)(50)(300)} = 0.0676 \text{ Wb}$$

Now flux, $\Phi_m = B_m \times A$, where A is the cross-sectional area of the core,

hence area, $\mathbf{A} = \left(\frac{\Phi_m}{B_m}\right) = \left(\frac{0.0676}{1.4}\right)$

$= \mathbf{0.0483\ m^2}$ or $\mathbf{483\ cm^2}$

Problems

1. 1. A 60 kVA, 1600 V/100 V, 50 Hz, single-phase transformer has 50 secondary windings. Calculate (a) the primary and secondary current, (b) the number of primary turns, and (c) the maximum value of the flux [(a) 37.5 A, 600 A (b) 800 (c) 9.0 mWb]
2. A single-phase, 50 Hz transformer has 40 primary turns and 520 secondary turns. The cross-sectional area of the core is 270 cm^2. When the primary winding is connected to a 300 volt supply, determine (a) the maximum value of flux density in the core, and (b) the voltage induced in the secondary winding [(a) 1.25 T (b) 3.90 kV]
3. A single-phase 800 V/100 V, 50 Hz transformer has a maximum core flux density of 1.294 T and an effective cross-sectional area of 60 cm 2 . Calculate the number of turns on the primary and secondary windings. [464, 58]
4. A 3.3 kV/110 V, 50 Hz, single-phase transformer is to have an approximate e.m.f. per turn of 22 V and operate with a maximum flux of 1.25 T. Calculate (a) the number of primary and secondary turns, and (b) the cross-sectional area of the core [(a) 150, 5 (b) 792.8 cm 2]

Practical Equivalent of Power Transformers

Transformer windings are made mainly of copper. Although copper is a very good conductor, it still has some internal resistance. Hence, both the primary and the secondary winding of a transformer have finite resistances viz. R_1 and R_2. These resistances spread uniformly throughout the windings and give rise to copper losses (I^2R). Let us consider that the emf I_1N_1 in the primary winding induces the flux Φ_{l1}, the emf I_2N_2 in the secondary windings, and the leakage flux Φ_{l2}. Both the magnetic reluctances of the fluxes of primary and secondary windings are equivalent to the leakage reactance of the transformer windings. They are series effects at very low (50Hz / 60Hz) operating frequencies. These can be regarded as lumped parameters for ease of calculations. Therefore, the transformer is considered to consist of lumped resistances R_1 and R_2, and reactance X_{l1} and X_{l2} in series with the respective windings; see Fig. 13.

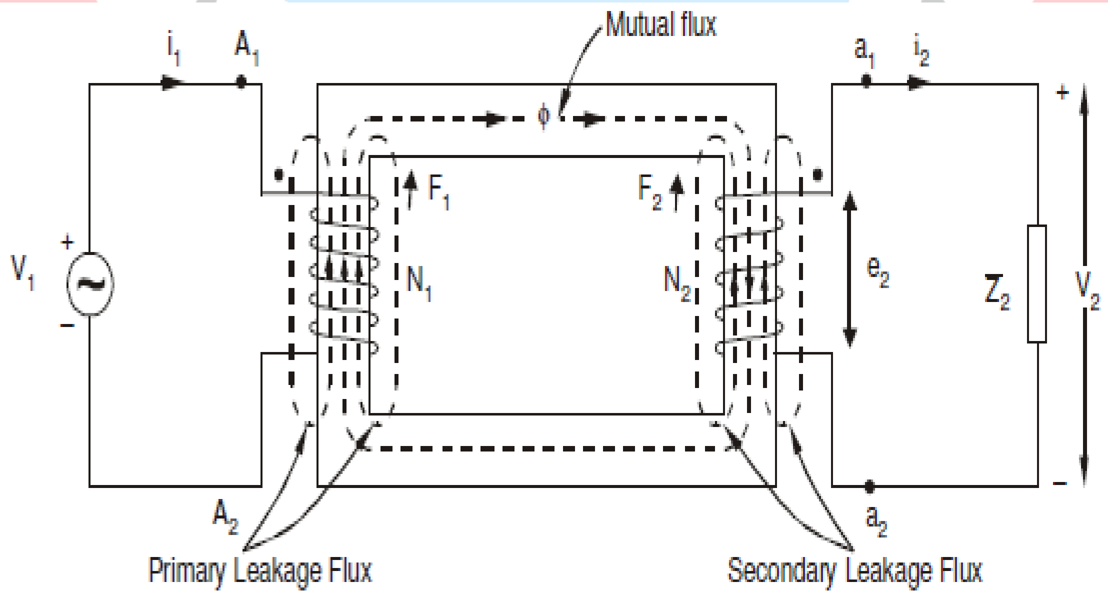


Fig. 13: Practical or non-ideal transformer

The induced emfs E_1 and E_2 may vary slightly from the secondary voltages V_1 and V_2 due to the presence of the lumped impedances. This phenomenon is observed due to small voltage drops in the winding resistances R_1 and R_2 as well as the leakage reactances. Recalling that the turns ratio TR = a = (N_1/N_2) = $(E_1/\ E_2)$ which can be approximated by $(V_1\ /\ V_2)$ with the voltage drops are neglected.

Now, the excitation current (I_0) can be divided into two components: the magnetizing current (I_m) and the core current (Ic). All currents and fluxes are phasor quantities. The magnetizing component creates mutual flux Φ that flow on the magnetizing reactance X_m (or its susceptance $B_m=1/X_m$), and I_c is the core loss component that provides the loss associated with alternating of the flux and it flows on the core resistance R_c (or its equivalent conductance $G_c = 1/R_c$). It can be represented as $\bar{I_0} = \bar{I_m} + \bar{I_c}$. Here vector form is indicated by the negative (¯) symbol. Hence, the equivalent circuit of a practical transformer can be represented as shown in Fig. 14. It is important to note that the shown equivalent circuit is valid for two-winding single-phase transformer, and also valid for representing the per-phase equivalent circuit of standard three-phase transformer (i.e. transformer with only primary and secondary sides).

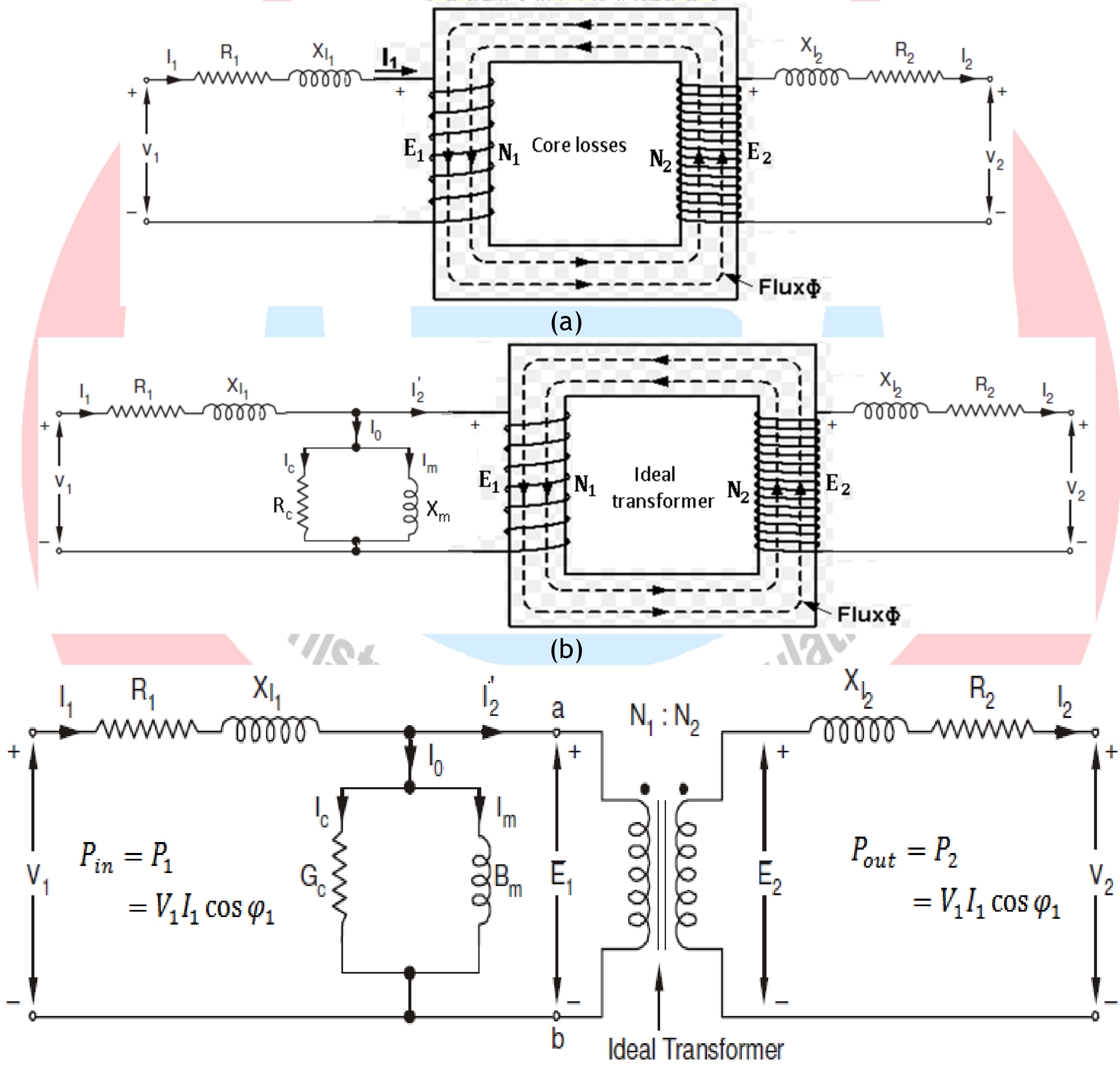


Fig. 14: Equivalent circuit of a practical transformer. (a) With winding parameters separated; (b) With winding and core parameters separated; (c) the equivalent circuit.

It is often convenient to assume that all of the resistance and reactance as being on one side of the transformer as shown in Fig. 15. This is can be done by using the referring that is based on the power conservation. The parameters of this equivalent circuit can be obtained as follows:

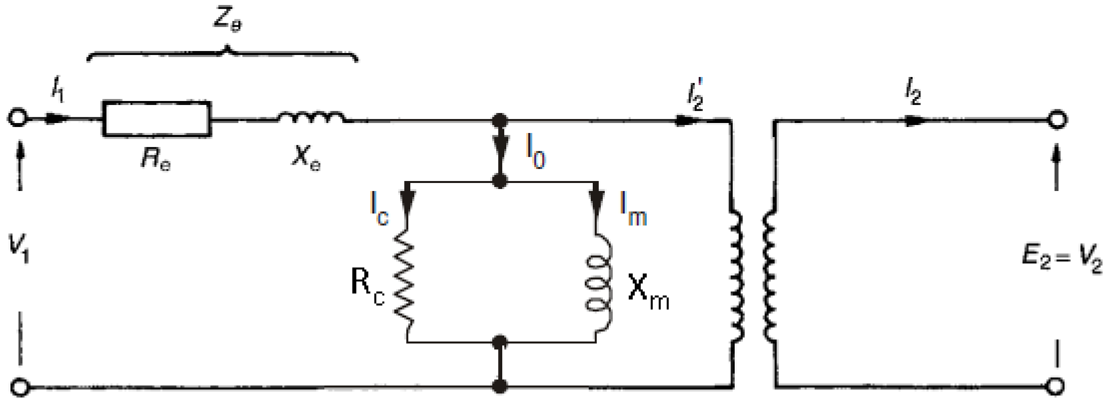


Fig. 15: Equivalent circuit referred to the primary side

$$I_1^2 R_2' = I_2^2 R_2 \quad (5)$$

$$R_2' = R_2 \left(\frac{I_2}{I_1}\right)^2 = R_2 \left(\frac{V_1}{V_2}\right)^2 \quad (6)$$

$$R_e = R_1 + R_2' \quad (7)$$

$$R_e = R_1 + R_2 \left(\frac{V_1}{V_2}\right)^2 \quad (8)$$

$$X_e = X_1 + X_2' \quad (9)$$

$$X_e = X_1 + X_2 \left(\frac{V_1}{V_2}\right)^2 \quad (10)$$

$$Z_e = \sqrt{R_e^2 + X_e^2} \quad (11)$$

$$\cos\phi_e = \frac{R_e}{Z_e} \quad (12)$$

Example11

A transformer has 600 primary turns and 150 secondary turns. The primary and secondary resistances are 0.25 Ω and 0.01 Ω respectively and the corresponding leakage reactances are 1.0 Ω and 0.04 Ω respectively. Determine:

a) The equivalent resistance referred to the primary winding,
b) The equivalent reactance referred to the primary winding,
c) The equivalent impedance referred to the primary winding, and
d) The phase angle of the impedance.

Solution

(a) From equation (6), equivalent resistance

$$R_e = R_1 + R_2 \left(\frac{V_1}{V_2}\right)^2$$

$$\text{i.e. } R_e = 0.25 + 0.01 \left(\frac{600}{150}\right)^2$$

$$= \mathbf{0.41\ \Omega} \text{ since } \frac{N_1}{N_2} = \frac{V_1}{V_2}$$

(b) From equation (7), equivalent reactance,

$$X_e = X_1 + X_2 \left(\frac{V_1}{V_2}\right)^2$$

$$\text{i.e. } X_e = 1.0 + 0.04 \left(\frac{600}{150}\right)^2 = \mathbf{1.64\ \Omega}$$

(c) From equation (8), equivalent impedance,

$$Z_e = \sqrt{R_e^2 + X_e^2} = \sqrt{0.41^2 + 1.64^2} = \mathbf{1.69\ \Omega}$$

(d) From equation (9),

$$\cos \phi_e = \frac{R_e}{Z_e} = \frac{0.41}{1.69}$$

$$\text{Hence } \boldsymbol{\phi_e} = \cos^{-1} \frac{0.41}{1.69} = \mathbf{75.96^\circ}$$

Problem

A transformer has 1200 primary turns and 200 turns. The primary and secondary resistance's are 0.2 Ω and 0.02 Ω respectively and the corresponding leakage reactance's are 1.2 Ω and 0.05 Ω respectively. Calculate (a) the equivalent resistance, reactance and impedance referred to the primary winding, and (b) the phase angle of the impedance.
[(a) 0.92 , 3.0 , 3.14 (b) 72.95°]

Power, Efficiency, and Regulation

A transformer does not require any moving parts to transfer energy. This means that there are no friction or windage losses associated with other electrical machines. However, transformers do suffer from other types of losses called "copper losses" and "iron losses" but generally these are quite small.

Copper losses, also known as I^2R loss is the electrical power which is lost in heat as a result of circulating the currents around the transformers copper windings, hence the name. Copper losses represents the greatest loss in the operation of a transformer. The actual watts of power lost can be determined (in each winding) by squaring the amperes and multiplying by the resistance in ohms of the winding (I^2R). Iron losses, also known as hysteresis is the lagging of the magnetic molecules within the core, in response to the alternating magnetic flux. This lagging (or out-of-phase) condition is due to the fact that it requires power to reverse magnetic molecules; they do not reverse until the flux has attained sufficient force to reverse them. Their reversal results in friction, and friction produces heat in the core which is a form of power loss. Hysteresis within the transformer can be reduced by making the core from special steel alloys.

The input and output power relations takes the form,

$$P_{in} = P_1 = V_1 I_1 \cos\varphi_1 \qquad (13)$$

$$P_{out} = P_2 = V_1 I_1 \cos\varphi_1 \qquad (14)$$

where cos φ1 and cos φ2 are the power factors of the input and output powers respectively.

Generally, the efficiency is defined as the (often measurable) ability to avoid wasting materials, energy, efforts, money, and time in doing something or in producing a desired result. In a more general sense, it is the ability to do things well, successfully, and without waste. In more mathematical or scientific terms, it is a measure of the extent to which input is well used for an intended task or function (output). Therefore, for a transformer, it is calculated as

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{input power - losses}}{\text{input power}} \qquad (15)$$

$$\eta = 1 - \frac{\text{losses}}{\text{input power}} \qquad (16)$$

It is not uncommon for power transformers to have efficiencies of between 95% and 98%.

Example12

A 200 kVA rated transformer has a full-load copper loss of 1.5 kW and an iron loss of 1 kW. Determine the transformer efficiency at full load and 0.85 power factor.

Solution

$$\text{Efficiency}, \eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{input power} - \text{losses}}{\text{input power}} = 1 - \frac{\text{losses}}{\text{input power}}$$

Full-load output power $= VI\cos\phi = (200)\ (0.85)$ $= 170\,\text{kW}$.

Total losses $= 1.5 + 1.0 = 2.5\,\text{kW}$

Input power $=$ output power $+$ losses $= 170 + 2.5 = 172.5\,\text{kW}$.

$$\text{Hence efficiency} = \left(1 - \frac{2.5}{172.5}\right) = 1 - 0.01449$$

$$= 0.9855 \text{ or } \mathbf{98.55\%}$$

Example13

Determine the efficiency of the transformer in the previous example at half full-load and 0.85 power factor.

Solution

Half full-load power output = (1/2)(200)(0.85) = 85 kW.

Copper loss (or I^2R loss) is proportional to current squared. Hence the copper loss at half full-load is: $\left(\frac{1}{2}\right)^2(1500) = 375$ W

Iron loss = 1000 W (constant)

Total losses = 375+1000=1375 W or 1.375 kW.

Input power at half full-load

= output power at half full-load + losses

= 85 + 1.375 = 86.375 kW. Hence

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input power}}$$

$$= \left(1 - \frac{1.375}{86.375}\right)$$

$$= 1 - 0.01592$$

$$= 0.9841 \text{ or } \mathbf{98.41\%}$$

Example14

A 400 kVA transformer has a primary winding resistance of 0.5 Ω and a secondary winding resistance of 0.001 Ω. The iron loss is 2.5 kW and the primary and secondary voltages are 5 kV and 320 V respectively. If the power factor of the load is 0.85, determine the efficiency of the transformer (a) on full load, and (b) on half load.

Solution

(a) Rating = 400 kVA = V_1I_1 = V_2I_2. Hence primary current,

$$I_1 = \frac{400 \times 10^3}{V_1} = \frac{400 \times 10^3}{5000} = 80\text{ A}$$

and secondary current,

$$I_2 = \frac{400 \times 10^3}{V_2} = \frac{400 \times 10^3}{320} = 1250\,\text{A}$$

Total copper loss $= I_1^2 R_1 + I_2^2 R_2$, (where $R_1 = 0.5\ \Omega$ and $R_2 = 0.001\ \Omega$)

$$= (80)^2(0.5) + (1250)^2(0.001)$$

$$= 3200 + 1562.5 = 4762.5 \text{ watts}$$

On full load, total loss = copper loss + iron loss

$$= 4762.5 + 2500 = 7262.5\,\text{W} = 7.2625\,\text{kW}$$

$$\text{Efficiency, } \eta = \left(1 - \frac{\text{losses}}{\text{input power}}\right) \times 100\%$$

$$= \left(1 - \frac{7.2625}{347.2625}\right) \times 100\%$$

$$= \mathbf{97.91\%}$$

(b) Since the copper loss varies as the square of the current, then total copper loss on half load $= 4762.5 \times \left(\frac{1}{2}\right)^2 = 1190.625\,\text{W}$. Hence total loss on half load $= 1190.625 + 2500 = 3690.625\,\text{W}$ or $3.691\,\text{kW}$.
Output power on half full load $= \left(\frac{1}{2}\right)(340) = 170\,\text{kW}$.
Input power on half full load
= output power + losses

$$= 170\,\text{kW} + 3.691\,\text{kW}$$

$$= 173.691\,\text{kW}$$

Hence efficiency at half full load,

$$\eta = \left(1 - \frac{\text{losses}}{\text{input power}}\right) \times 100\%$$

$$= \left(1 - \frac{3.691}{173.691}\right) \times 100\% = \mathbf{97.87\%}$$

When the secondary of a transformer is loaded, the secondary terminal voltage (V_2) falls. As the power factor decreases, this voltage drop increases. This is called the ***regulation of the transformer*** and it is usually ***expressed as a percentage of the secondary no-load voltage*** (E_2). For full-load conditions:

$$\textbf{Regulation} = \left(\frac{E_2 - V_2}{E_2}\right) \times 100\% \qquad (17)$$

Example 15

A 5 kVA, 200 V/400 V, single-phase transformer has a secondary terminal voltage of 387.6 volts when loaded. Determine the regulation of the transformer.

Solution

$$\text{regulation} = \left(\frac{\text{No load secondary voltage} - \text{terminal voltage on load}}{\text{no load secondary voltage}}\right) 100\%$$

$$= \left(\frac{400 - 387.6}{400}\right) \times 100\%$$

$$= \left(\frac{12.4}{400}\right) \times 100\%$$

$$= \mathbf{3.1\%}$$

Example 16

The open circuit voltage of a transformer is 240 V. A tap changing device is set to operate when the percentage regulation drops below 2.5%. Determine the load voltage at which the mechanism operates.

Solution

$$\text{Regulation} = \left(\frac{\text{No load secondary voltage} - \text{terminal voltage on load}}{\text{no load secondary voltage}}\right) 100\%$$

Hence $$2.5 = \left(\frac{240 - V_2}{240}\right) \times 100\%$$

$$\therefore \quad \frac{(2.5)(240)}{100} = 240 - V_2$$

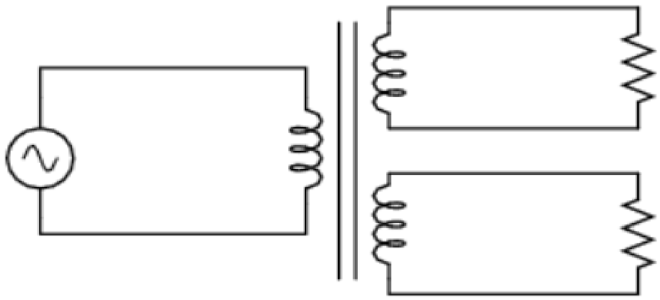
i.e. $$6 = 240 - V_2$$

from which, **load voltage,** $\boldsymbol{V_2} = 240 - 6 = \mathbf{234}$ **volts**

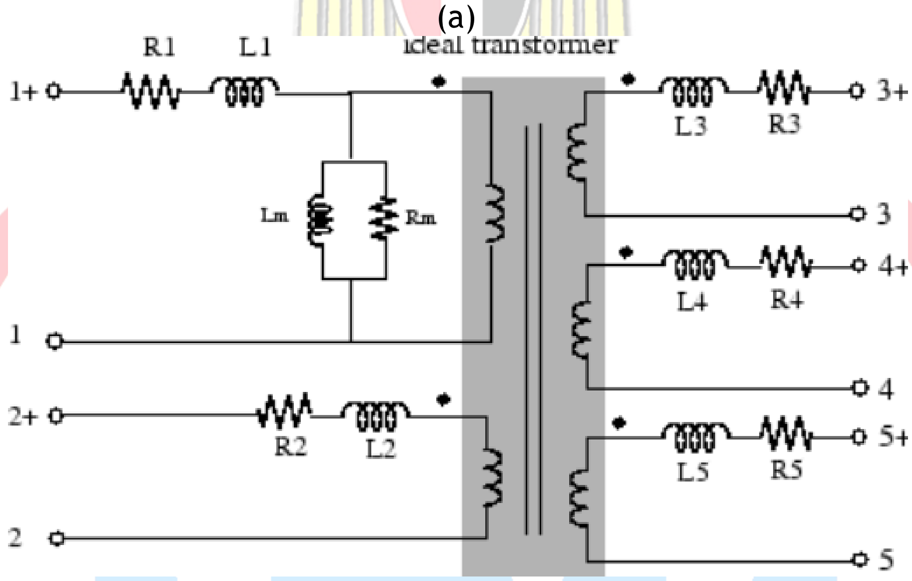
Problems

1. A 6 kVA, 100 V/500 V, single-phase transformer has a secondary terminal voltage of 487.5 volts when loaded. Determine the regulation of the transformer. [2.5%]
2. A transformer has an open circuit voltage of 110 volts. A tap-changing device operates when the regulation falls below 3%. Calculate the load voltage at which the tap-changer operates. [106.7 volts]
3. A single-phase transformer has a voltage ratio of 6:1 and the h.v. winding is supplied at 540 V. The secondary winding provides a full load current of 30 A at a power factor of 0.8 lagging. Neglecting losses, find (a) the rating of the transformer, (b) the power supplied to the load, (c) the primary current. [(a) 2.7 kVA (b) 2.16 kW (c) 5 A]
4. A single-phase transformer is rated at 40 kVA. The transformer has full-load copper losses of 800 W and iron losses of 500 W. Determine the transformer efficiency at full load and 0.8 power factor [96.10%]
5. Determine the efficiency of the transformer in problem 2 at half full-load and 0.8 power factor [95.81%]
6. A 100 kVA, 2000 V/400 V, 50 Hz, single-phase transformer has an iron loss of 600 W and a full-load copper loss of 1600 W. Calculate its efficiency for a load of 60 kW at 0.8 power factor. [97.56%]

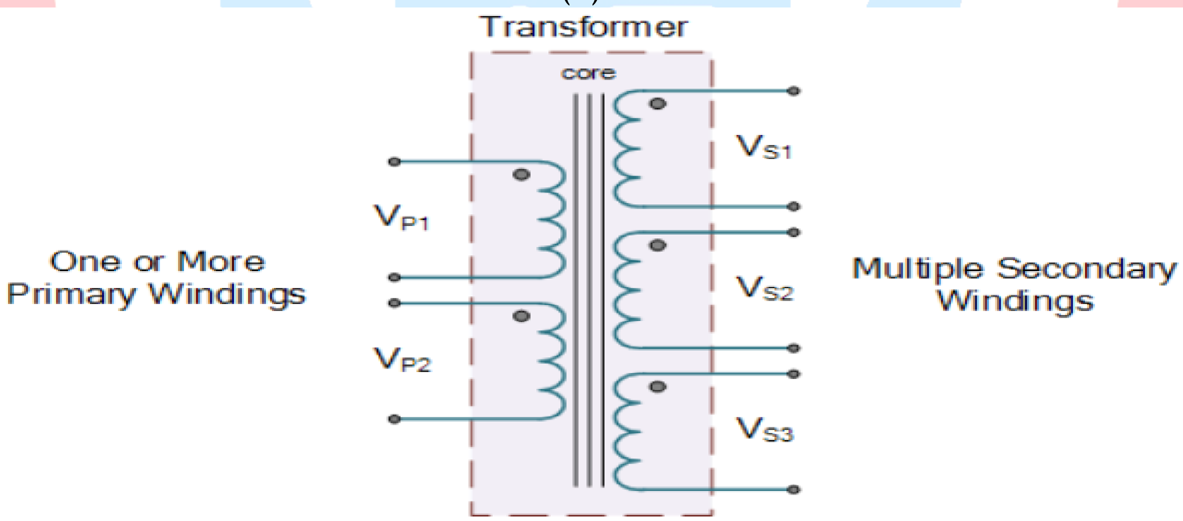
Multi-winding single-phase transformers



(a)



(b)



(c)

Fig. 16: Examples of multi winding transformers

Multiple Winding Transformers generally have one single primary winding with two or more secondary windings. The beauty of transformers is that they allow us to have more than just one winding in either the primary or secondary side; this is called ***Multiple Winding Transformers***. Multiple Winding Transformers have many uses in electrical and electronic circuits. They can be used to supply different secondary voltages to different medical and industrial loads. Have their windings connected together in series or parallel combinations to provide higher voltages or currents, or have their secondary windings connected together in series to produce a center tapped transformer.

The principal of operation of a multiple winding transformer is no different from that of an ordinary transformer. Primary and secondary voltages, currents and turns ratios are all calculated the same, the difference this time is that we need to pay special attention to the voltage polarities of each coil winding, the dot convention marking the positive (or negative) polarity of the winding, when we connect them together. Multiple winding transformers, also known as a ***multi-coil**, **or multi-winding transformer***, contain more than one primary or more than one secondary coil, hence their name, on a common laminated core. They can be a single-phase transformer or a three-phase transformer, (multi-winding, multi-phase transformer) the operation is the same. Examples of multi winding transformers are shown in Fig. 16.

In the above shows an example of a typical "multiple winding transformer" which has a number of different secondary windings supplying various voltage levels. The primary windings can be used individually or connected together to operate the transformer from a higher supply voltages. The secondary windings can be connected together in various configurations producing a higher voltage or current supply. It must be noted that connecting together in parallel transformer windings is only possible if the two windings are electrically identical. That is their current and voltage ratings are the same.

Multiple Winding Transformers can also be used to provide either a step-up, a step-down, or a combination of both between the various windings. In fact a multiple winding transformers can have several secondary windings on the same core with each one providing a different voltage or current level output. As transformers operate on the principal of mutual induction, each individual winding of a multiple winding transformer supports the same number of volts per turn, therefore the volt-ampere product in each winding is the same, that is $N_P/N_S = V_P/V_S$ with any turns ratio between the individual coil windings being relative to the primary supply. In electronic circuits, one transformer is often used to supply a variety of lower voltage levels for different components in the electronic circuitry. A typical application of multiple winding transformers is in power supplies and triac switching converters. So a transformer may have a number of different secondary windings, each of which is electrically isolated from the others, just as it is electrically isolated from the primary. Then each of the secondary coils will produce a voltage that is proportional to its number of coil turns for example.

There are a number or multiple winding transformers available which have two primary windings of identical voltage and current ratings and two secondary windings also with identical voltage and current ratings. These transformers are designed so that they can be used in a variety of applications with the windings connected together in either a series or parallel combinations for higher primary voltages or secondary currents. These types of multiple winding transformers are more commonly called ***Dual Voltage Transformers*** as shown in Fig. 17.

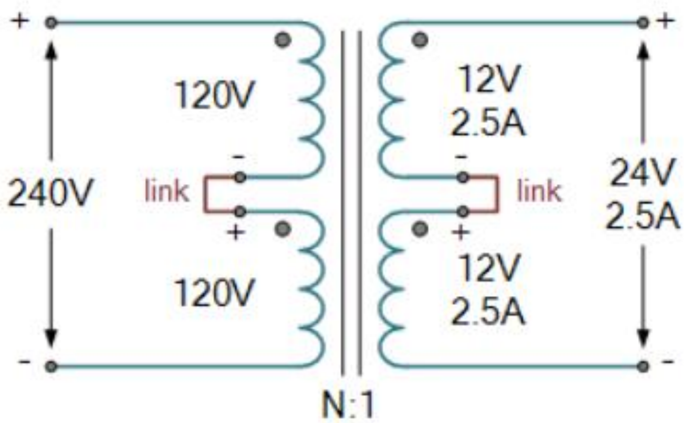


Fig. 17: An example of dual voltage transformer

Dual Primary & Dual Secondary Transformer. Here the transformer has two primary windings and two secondary windings, four in total. The connections to the primary or secondary windings must be made correctly with dual voltage transformers. If connected improperly, it is possible to create a dead short that will usually destroy the transformer when it is energized. We said previously that dual voltage transformers can be connected to operate from power supplies of different voltage levels, hence their name "dual voltage transformers" as shown in Fig. 18. Then for example, lets say that the primary winding could have a voltage rating of 240/120V on the primary and 12/24V on the secondary as shown in Fig. 17. To achieve this, each of the two primary windings is, therefore, rated at 120V, and each secondary winding is rated at 12V. The transformer must be connected so that each primary winding receives the proper voltage.

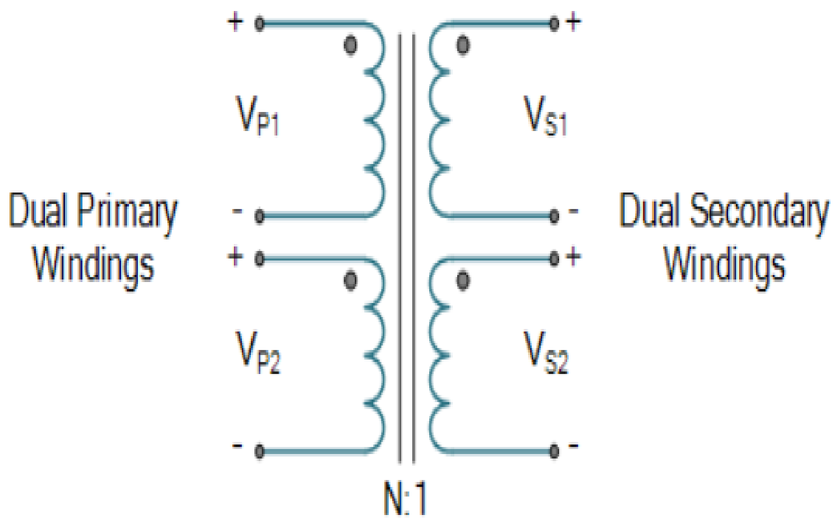


Fig. 18: Dual primary & dual secondary transformer

Series Connected Secondary Transformer. Here in this example shown in Fig. 17, the two 120V rated primary windings are connected together in series across a 240V supply as the two windings are identical, half the supply voltage, namely 120V, is dropped across each winding and the same primary current flows through both. The two secondary windings rated at 12V, 2.5A each are connected in series with the secondary terminal voltage being the sum of the two individual winding voltages giving 24 Volts. As the two windings are connected in series, the same amount of current flows through each winding, then the secondary current is the same at 2.5 Amps. So for a series connected secondary, the output in our example above is rated at 24 Volts, 2.5 Amps.

Parallel Connected Secondary Transformer. Here we have kept the two primary windings the same but the two secondary windings are now connected in a parallel combination; Fig. 19. As before, the two secondary windings are rated at 12V, 2.5A each, therefore the secondary terminal voltage will be the same at 12 Volts but the current adds. Then for a parallel connected secondary, the output in our example above is rated at 12 Volts, 5.0 Amps.

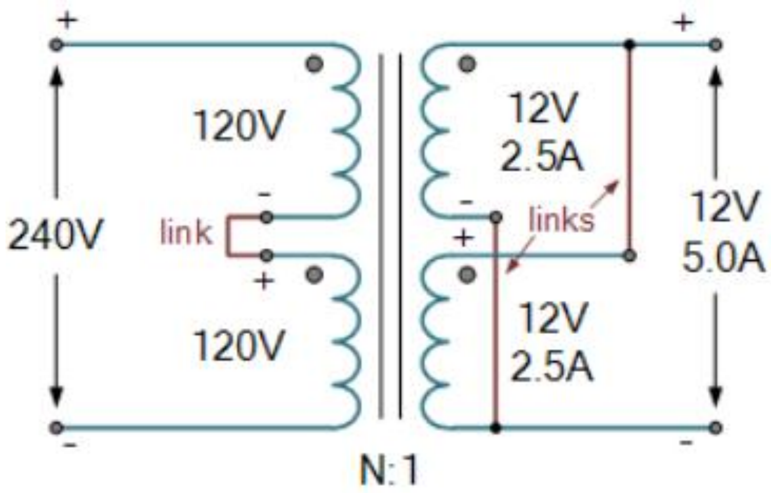


Fig. 19: Parallel connected secondary transformer

Of course different dual voltage transformers will produce different amounts of secondary voltage and current but the principal is the same. Secondary windings must be correctly connected together to produce the required voltage or current output. Dot orientation is used on the windings to indicate the terminals that have the same phase relationship. For example connecting two secondary windings together in opposite dot-orientation will cause the two magnetic flux's to cancel each other out resulting in zero output.

A ***center-tap transformer*** is designed to provide two separate secondary voltages, VA and VB with a common connection; Fig. 20. This type of transformer configuration produces a two-phase, 3-wire supply. The secondary voltages are the same and proportional to the supply voltage, VP, therefore power in each winding is the same. The voltages produced across each of the secondary winding is determined by the turns ratio as shown.

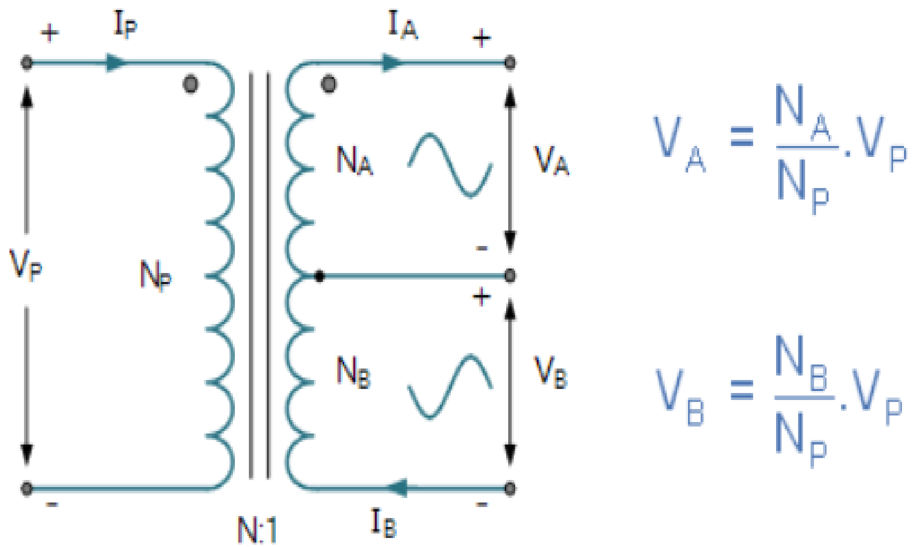


Fig. 20: Center-tap transformer

Above shows a typical center-tap transformer. The tapping point is in the exact center of the secondary winding providing a common connection for two equal but opposite secondary voltages. With the center-tap grounded, the output VA will be positive in nature with respect to the ground, while the voltage at the other secondary, VB will be negative and opposite in nature, that is they are 180o electrical degrees out-of-phase with each other; however, there is one disadvantage of using an ungrounded center tapped transformer and that is it can produce unbalanced voltages in the two secondary windings due to unsymmetrical currents flowing in the common third connection because of unbalanced loads.

We can also produce a center-tap transformer using the dual voltage transformer from above; Fig. 21. By connecting the secondary windings in series, we can use the center link as the tap as shown. If the output from each secondary is V, the total output voltage for the secondary winding will be equal to 2V as shown.

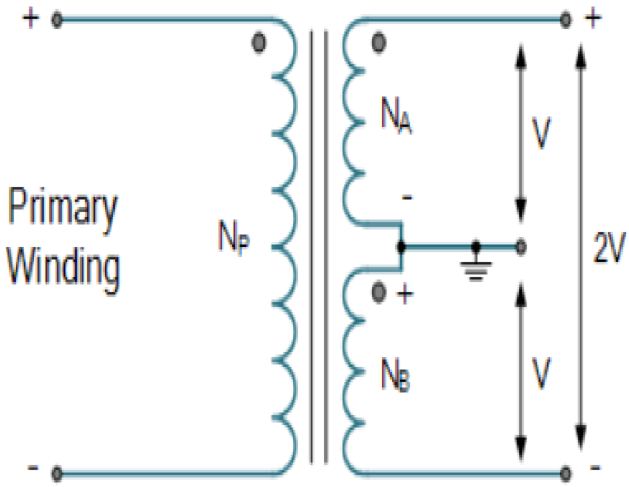
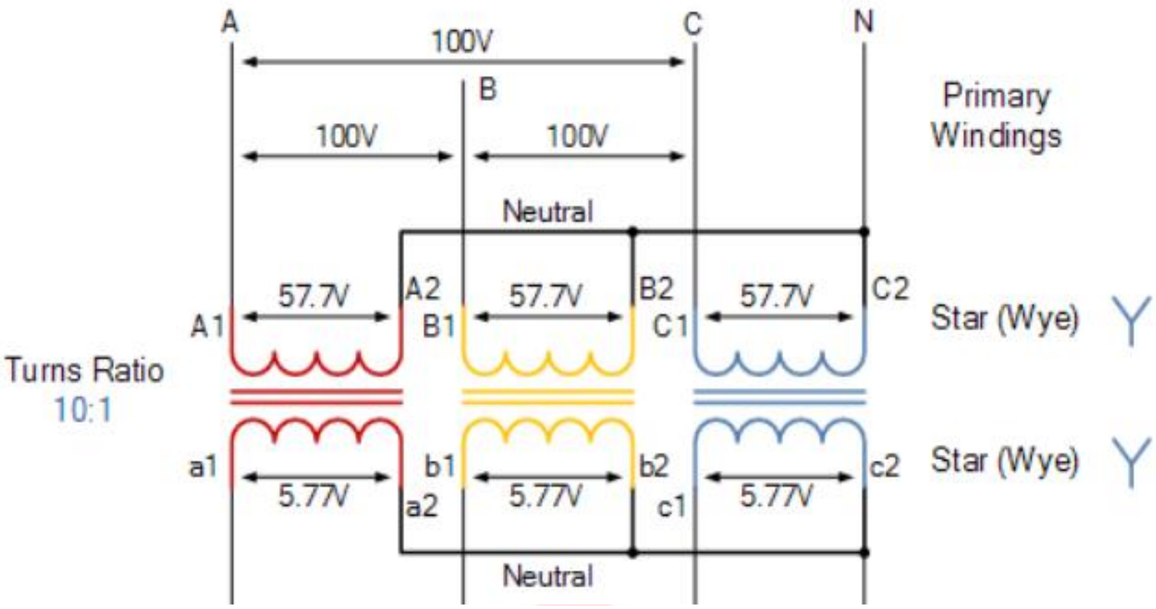


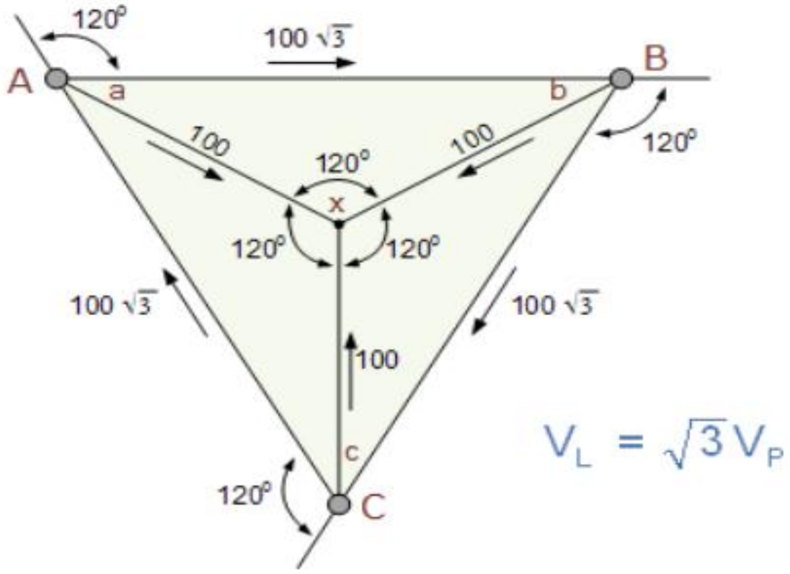
Fig. 21: Center-tap transformer using the dual voltage transformer

Three-phase Transformers

Three-phase Transformers are the backbone of electrical power distribution. Thus far we have mainly looked at the construction and operation of the single-phase, two winding voltage transformer which can be used increase or decrease its secondary voltage with respect to the primary supply voltage. But voltage transformers can also be constructed for connection to not only one single phase, but for two-phases, three-phases, six-phases and even elaborate combinations up to 24-phases for some DC rectification transformers.



(a)



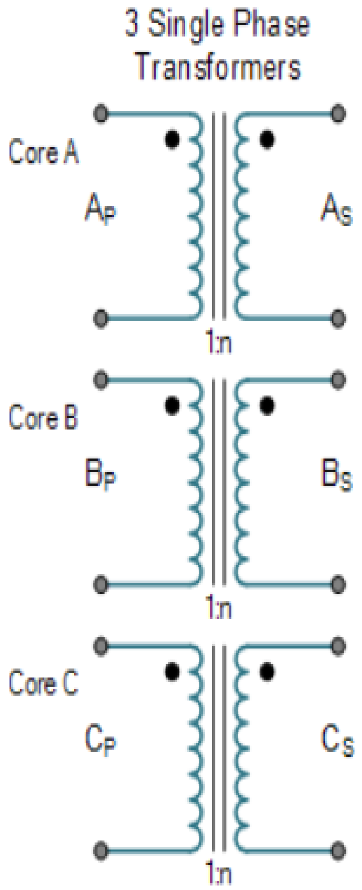
(b)

Fig. 22: Three-phase transformer example. (a) Connection of windings; (b) Voltage phasors

If we take three single-phase transformers and connect their primary windings to each other and their secondary windings to each other in a fixed configuration, we can use the transformers on a three-phase supply. Three-phase, also written as 3-phase or 3φ supplies are used for electrical power generation, transmission, and distribution, as well as for all industrial applications. Three-phase supplies have many electrical advantages over single-phase power and when considering three-phase transformers we have to deal with three alternating voltages and currents differing in phase-time by 120 degrees as shown in the example of Fig. 22 where V_L is the line-to-line voltage, and V_P is the phase-to-neutral voltage.

A transformer cannot act as a phase changing device and change single-phase into three-phase or three-phase into single phase. To make the transformer connections compatible with three-phase supplies we need to connect them together in a particular way to form a ***Three Phase Transformer Configuration***.

A three phase transformer or 3φ transformer can be constructed either by connecting together three single-phase transformers, thereby forming a so-called ***three phase transformer bank***, or by using one pre-assembled and balanced three phase transformer which consists of three pairs of single phase windings mounted onto one single laminated core. The advantages of building a single three phase transformer is that for the same kVA rating it will be smaller, cheaper and lighter than three individual single phase transformers connected together because the copper and iron core are used more effectively. The methods of connecting the primary and secondary windings are the same, whether using just one Three Phase Transformer or three separate Single Phase Transformers. Consider the circuit of Fig. 23.



Primary Configuration	Secondary Configuration
Delta (Mesh) △	Delta (Mesh) △
Delta (Mesh) △	Star (Wye) Y
Star (Wye) Y	Delta (Mesh) △
Star (Wye) Y	Star (Wye) Y
Interconnected Star	Delta (Mesh) △
Interconnected Star	Star (Wye) Y

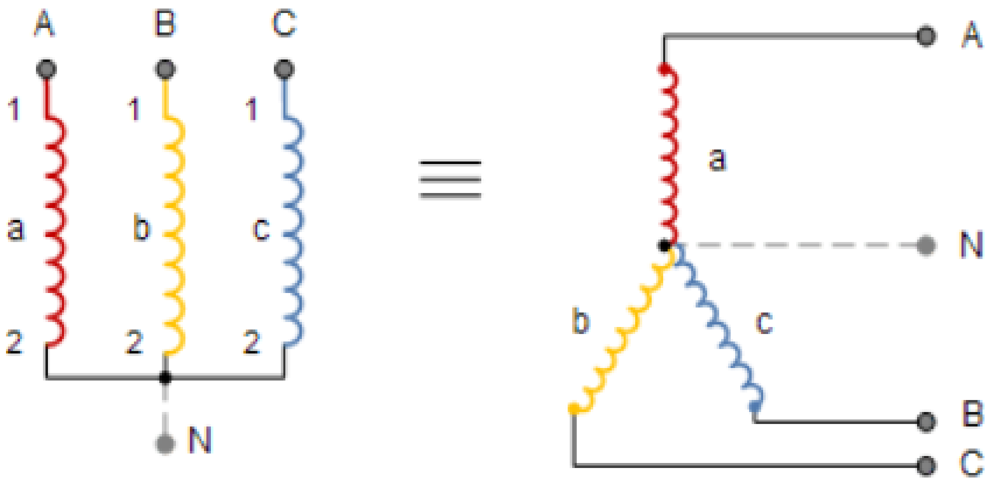
Fig. 23: Three-phase transformer connections

The primary and secondary windings of a transformer can be connected in different configuration as shown to meet practically any requirement. In the case of three phase transformer windings, three forms of connection are possible: “star” (wye), “delta” (mesh) and “interconnected-star” (zig-zag). The combinations of the three windings may be with the primary delta-connected and the secondary star-connected, or star-delta, star-star or delta-delta, depending on the transformers use. When transformers are used to provide three or more phases they are generally referred to as a ***Polyphase Transformer***.

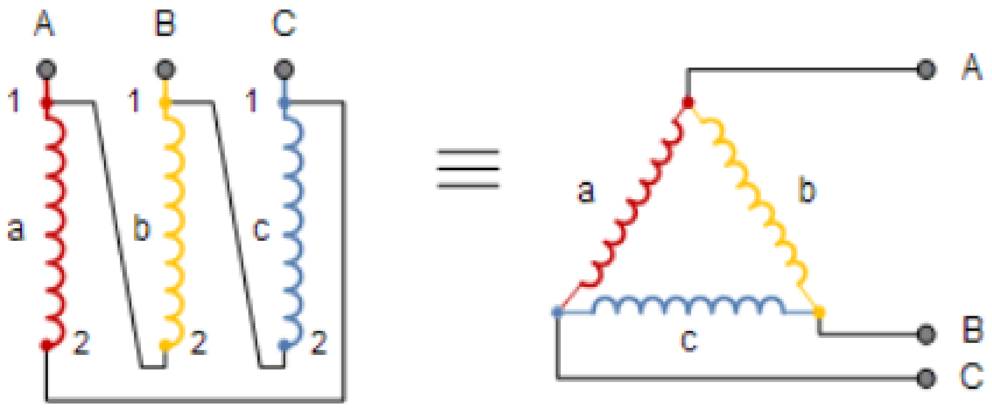
Three Phase Transformer Star and Delta Configurations

What do we mean by “star” (also known as Wye) and “delta” (also known as Mesh) when dealing with three-phase transformer connections? A three phase transformer has three sets of primary and secondary windings. Depending upon how these sets of windings are interconnected, determines whether the connection is a star or delta configuration. The three available voltages, which themselves are each displaced from the other by 120 electrical degrees, not only decided on the type of the electrical connections used on both the primary and secondary sides, but determine the flow of the transformers currents.

With three single-phase transformers connected together, the magnetic flux’s in the three transformers differ in phase by 120 time-degrees. With a single the three-phase transformer there are three magnetic flux’s in the core differing in time-phase by 120 degrees.



(a) Star Connection



(b) Delta Connection

Fig. 24: Star and delta connections of three-phase windings

The standard method for marking three phase transformer windings is to label the three primary windings with capital (upper case) letters A, B and C, used to represent the three individual phases of RED, YELLOW , and BLUE. The secondary windings are labeled with small (lower case) letters a, b and c. Each winding has two ends normally labeled 1 and 2 so that, for example, the second winding of the primary has ends which will be labeled B1 and B2, while the third winding of the secondary will be labeled c1 and c2 as shown in Fig. 24.

Symbols are generally used on a three phase transformer to indicate the type or types of connections used with upper case Y for star connected, D for delta connected and Z for interconnected star primary windings, with lower case y, d and z for their respective secondaries. Then, Star-Star would be labeled Yy, Delta-Delta would be labeled Dd and interconnected star to interconnected star would be Zz for the same types of connected transformers. This is summarized in Table 1.

Table 1: Symbols of various connections

Connection	Primary Winding	Secondary Winding
Delta	D	d
Star	Y	y
Interconnected	Z	z

We now know that there are four different ways in which three single-phase transformers may be connected together between their primary and secondary three-phase circuits. These four standard configurations are given as: Delta-Delta (Dd), Star-Star (Yy), Star-Delta (Yd), and Delta-Star (Dy). Transformers for high voltage operation with the star connections has the advantage of reducing the voltage on an individual transformer, reducing the number of turns required and an increase in the size of the conductors, making the coil windings easier and cheaper to insulate than delta transformers.

The delta-delta connection (Fig. 25) nevertheless has one big advantage over the star-delta configuration, in that if one transformer of a group of three should become faulty or disabled, the two remaining ones will continue to deliver three-phase power with a capacity equal to approximately two thirds of the original output from the transformer unit.

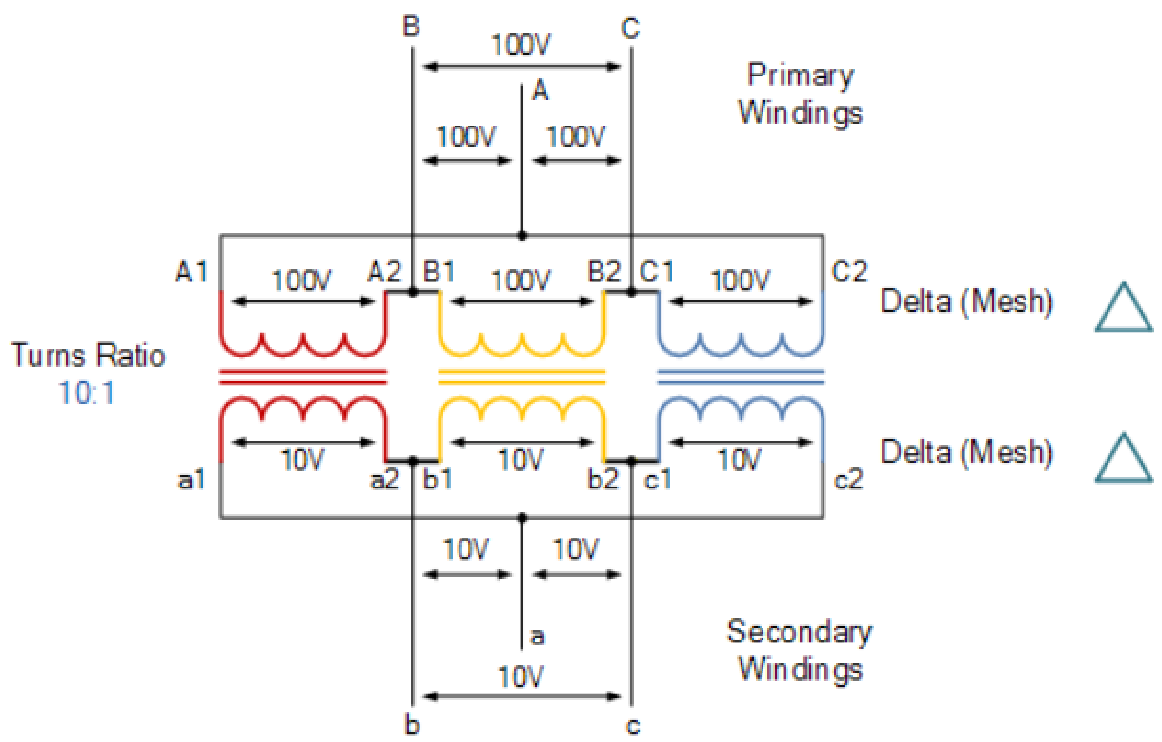


Fig. 25: Dd connection

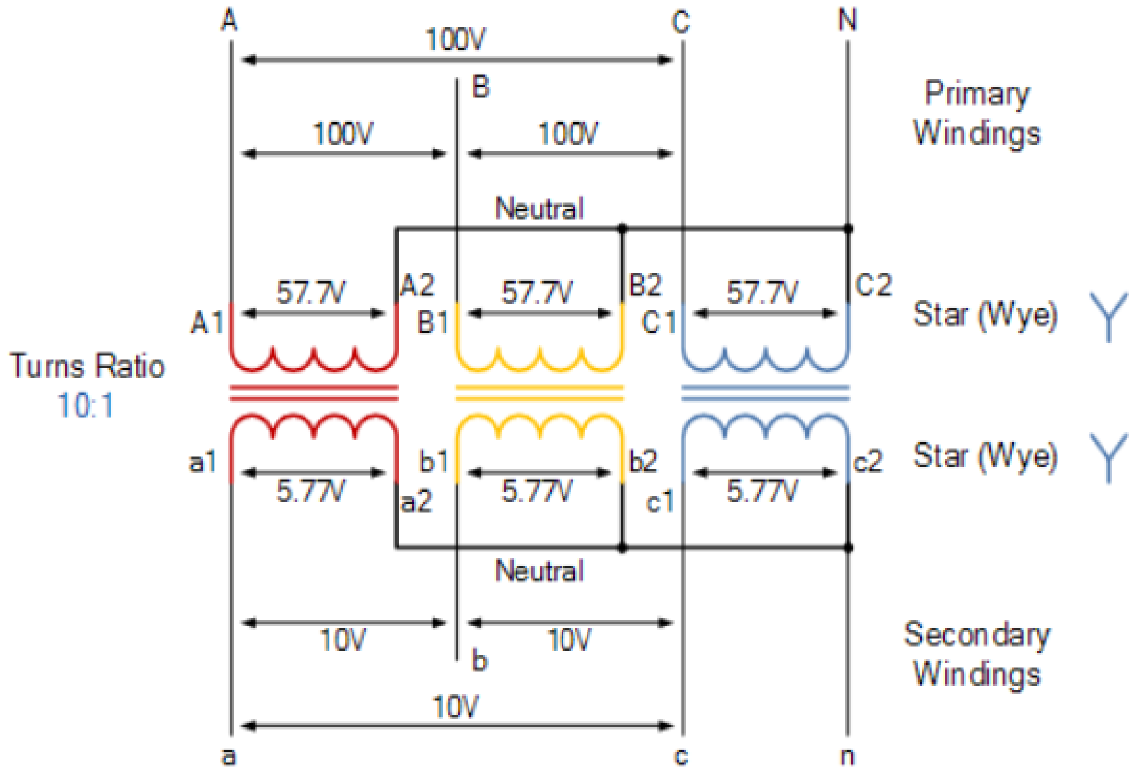


Fig. 26: Yy connection

In a delta connected (Dd) group of transformers, the line voltage, V_L is equal to the supply voltage, $V_L = V_S$. But the current in each phase winding is given as: $1/\sqrt{3} \times I_L$ of the line current, where I_L is the line current.

One disadvantage of delta connected three phase transformers is that each transformer must be wound for the full-line voltage, (in our example above 100V) and for 57.7 per cent, line current. The greater number of turns in the winding, together with the insulation between turns, necessitate a larger and more expensive coil than the star connection. Another disadvantage with delta connected three phase transformers is that there is no "neutral" or common connection.

In the star-star arrangement (Yy), (wye-wye), Fig. 26, each transformer has one terminal connected to a common junction, or neutral point with the three remaining ends of the primary windings connected to the three-phase mains supply. The number of turns in a transformer winding for star connection is 57.7 per cent, of that required for delta connection. The star connection requires the use of three transformers, and if any one transformer becomes fault or disabled, the whole group might become disabled. Nevertheless, the star connected three phase transformer is especially convenient and economical in electrical power distributing systems, in that a fourth wire may be connected as a neutral point, (n) of the three star connected secondaries as shown.

The voltage between any line of the three-phase transformer is called the "line voltage", V_L, while the voltage between any line and the neutral point of a star connected transformer is called the "phase voltage", V_P. This phase voltage between the neutral point and any one of the line connections is $1/\sqrt{3} \times V_L$ of the line voltage. The secondary current in each phase of a star-connected group of transformers is the same as that for the line current of the supply, then $I_L = I_S$.

The voltage and current relations in three-phase systems are summarized in Table 2 where again, V_L is the line-to-line voltage, and V_P is the phase-to-neutral voltage on either the primary or the secondary side.

Table 2: Voltage and current relations in three-phase systems

Connection	Phase Voltage	Line Voltage	Phase Current	Line Current
Star	$V_P = V_L \div \sqrt{3}$	$V_L = \sqrt{3} \times V_P$	$I_P = I_L$	$I_L = I_P$
Delta	$V_P = V_L$	$V_L = V_P$	$I_P = I_L \div \sqrt{3}$	$I_L = \sqrt{3} \times I_P$

Other possible connections for three phase transformers are star-delta Yd, where the primary winding is star-connected and the secondary is delta-connected or delta-star Dy with a delta-connected primary and a star-connected secondary. Delta-star connected transformers are widely used in low power distribution with the primary windings providing a three-wire balanced load to the utility company while the secondary windings provide the required 4th-wire neutral or earth connection.

When the primary and secondary have different types of winding connections, star or delta, the overall turns ratio of the transformer becomes more complicated. If a three-phase transformer is connected as delta-delta (Dd) or star-star (Yy) then the transformer could potentially have a 1:1 turns ratio. That is the input and output voltages for the windings are the same. However, if the 3-phase transformer is connected in star-delta, (Yd) each star-connected primary winding will receive the phase voltage, V_P of the supply, which is equal to $1/\sqrt{3} \times V_L$. Then, each corresponding secondary winding will then have this same voltage induced in it, and since these windings are delta-connected, the voltage $1/\sqrt{3} \times V_L$ will become the secondary line voltage. Then, with a 1:1 turns ratio, a star–delta connected transformer will provide a $\sqrt{3}$:1 step-down line-voltage ratio. Theerefore, for a star-delta (Yd) connected transformer the turns ratio becomes:

$$TR = a = \frac{N_p}{N_s} = \frac{V_p}{\sqrt{3}V_s} \quad (18)$$

Likewise, for a delta-star (Dy) connected transformer, with a 1:1 turns ratio, the transformer will provide a 1:$\sqrt{3}$ step-up line-voltage ratio. Therefore, for a delta-star connected transformer the turns ratio becomes:

$$TR = a = \frac{N_p}{N_s} = \frac{\sqrt{3}V_p}{V_s} \quad (19)$$

Table 3: Voltage and current relations

Primary-Secondary Configuration	Line Voltage Primary or Secondary	Line Current Primary or Secondary
Delta – Delta	$V_L \Rightarrow nV_L$	$I_L \Rightarrow \frac{I_L}{n}$
Delta – Star	$V_L \Rightarrow \sqrt{3}.nV_L$	$I_L \Rightarrow \frac{I_L}{\sqrt{3}.n}$
Star – Delta	$V_L \Rightarrow \frac{nV_L}{\sqrt{3}}$	$I_L \Rightarrow \sqrt{3}.\frac{I_L}{n}$
Star – Star	$V_L \Rightarrow nV_L$	$I_L \Rightarrow \frac{I_L}{n}$

For the four basic configurations of a three-phase transformer, the transformers secondary voltages and currents with respect to the primary line voltage, V_L and its primary line current I_L as shown in Table 3; where n equals the transformers “turns ratio” (T.R.) of the number of secondary windings N_S, divided by the number of primary windings N_P. (N_S/N_P) and V_L is the line-to-line voltage with V_P being the phase-to-neutral voltage.

Example 17

The primary winding of a delta-star (Dy) connected 50VA transformer is supplied with a 100 volt, 50Hz three-phase supply. If the transformer has 500 turns on the primary and 100 turns on the secondary winding, calculate the secondary side voltages and currents.

Solution

Given Data: transformer rating, 50VA, supply voltage, 100v, primary turns 500, secondary turns, 100.

$$n = \frac{N_S}{N_P} = \frac{100}{500} = 0.2$$

$$\begin{aligned} V_{L(sec)} &= \sqrt{3} \times n \times V_{L(pri)} \\ &= \sqrt{3} \times 0.2 \times 100 \\ &= 34.64\,\text{Volts} \end{aligned}$$

$$V_{P(sec)} = \frac{V_{L(sec)}}{\sqrt{3}} = \frac{34.64}{\sqrt{3}} = 20\,\text{Volts}$$

$$I_{L(pri)} = \frac{VA}{\sqrt{3}V_{L(pri)}} = \frac{50}{\sqrt{3} \times 100} = 0.289\,\text{Amps}$$

$$I_{sec} = \frac{I_{L(pri)}}{\sqrt{3} \times n} = \frac{0.289}{\sqrt{3} \times 0.2} = 0.834\,\text{Amps}$$

Therefore, the secondary side of the transformer supplies a line voltage, V_L of about 35 V giving a phase voltage, V_P of 20 V at 0.834 amperes.

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Parts of a Practical Power Transformer

Power Transformers are made up of lots of different parts performing different functions. Every big and tiny part of a transformer plays a very vital role in its functioning. Listed below are some of the most important parts of power transformers. Fig. 27 and Fig. 28 show examples of the main parts of an oil-filled power transformer. The function(s) of major parts will be described later in this section; however, the assembly of various transformers are different according to the manufacturer technologies, their types, and functions. Therefore, the students are encouraged to carefully inspect the transformers in the power substation that will be visited as a part of this course.

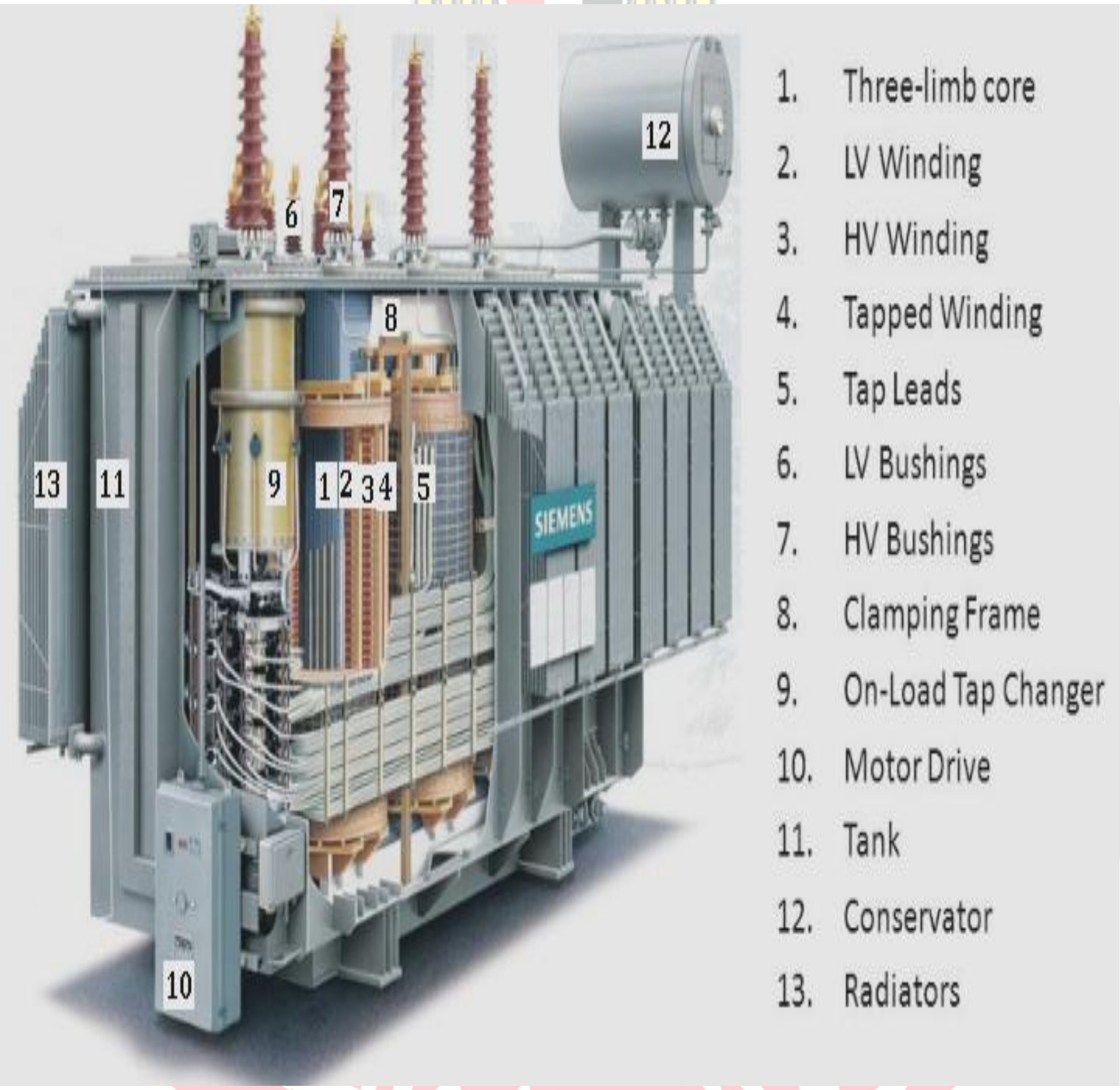
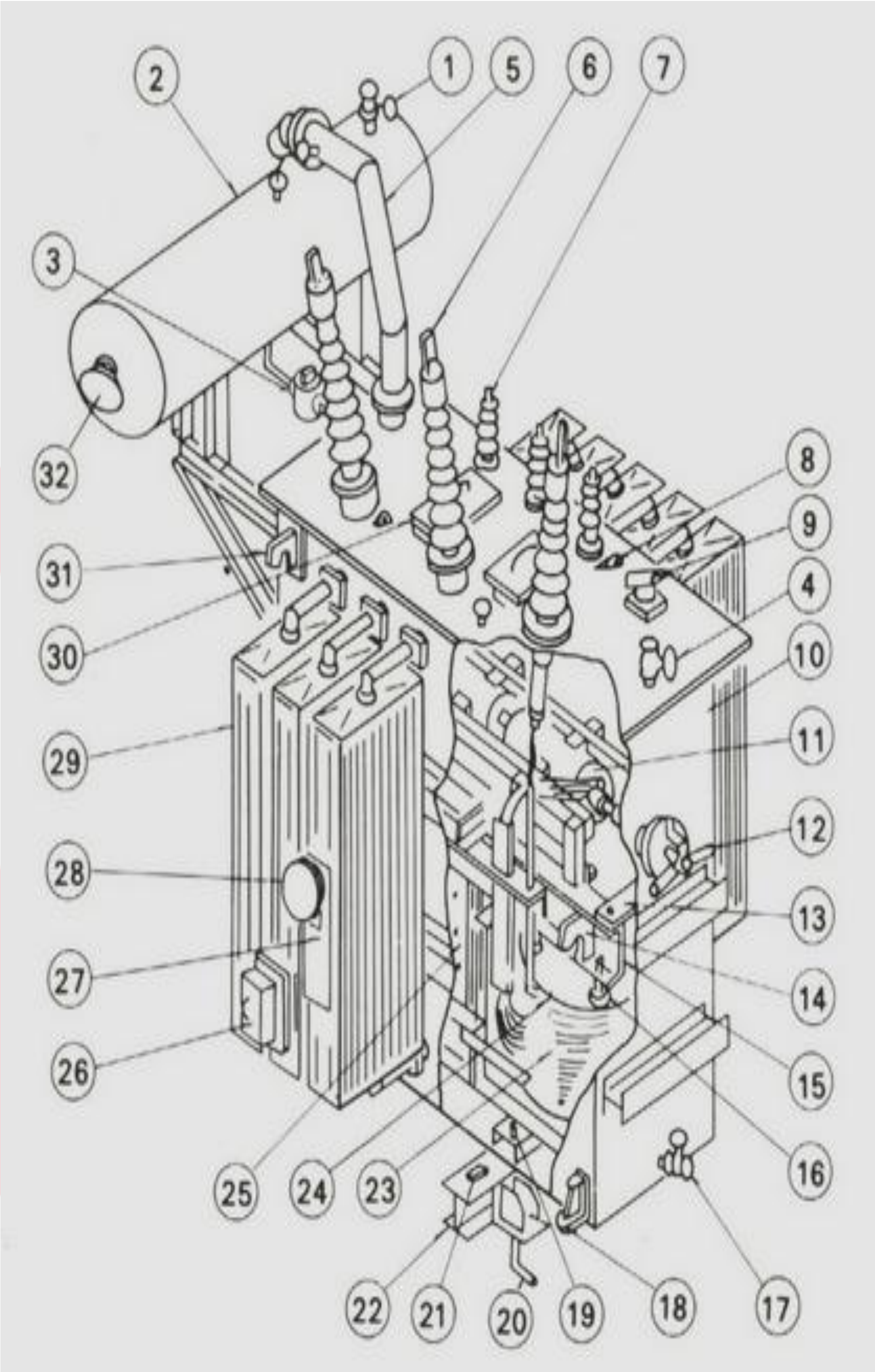


Fig. 27: Assembly of a large three-phase transformer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(a)

1	Oil filter valve	17	Oil drain valve
2	Conservator	18	Jacking boss
3	Buchholz relay	19	Stopper
4	Oil filter valve	20	Foundation bolt
5	Pressure-relief vent	21	Grounding terminal
6	High-voltage bushing	22	Skid base
7	Low-voltage bushing	23	Coil
8	Suspension lug	24	Coil pressure plate
9	B C T Terminal	25	Core
10	Tank	26	Terminal box for protective devices
11	De-energized tap changer	27	Rating plate
12	Tap changer handle	28	Dial thermometer
13	Fastener for core and coil	29	Radiator
14	Lifting hook for core and coil	30	Manhole
15	End frame	31	Lifting hook
16	Coil pressure bolt	32	Dial type oil level gauge

(b)

Fig. 27: Parts of an oil-filled power transformer and their names

The functions of some parts of oil-filled transformers are listed in the following.

1. ***Steel tank***. The most important part of a transformer, the steel tank is cylindrical or cubical, and holds the core, windings and other important devices of the transformer. It is coated with color internally and externally for safety and protection; and is usually filled with insulating oil, except for air transformers.
2. ***Conservator***. Connected above the main tank of the transformer, the conservator is a metallic cylindrical airtight drum that conserves the transformer oil. The normal oil level within the conservator is in the middle to allow the oil to expand or contract with temperature variations. The conservator helps to reduce oxidation by reducing the area of air around the oil.
3. ***Buchholz Relay***. The Buchholz Relay is protective device that is connected to a pipe between the main tank and conservator to sense faults occurring within the transformer. It operates due to the gases emitted owing to the decomposition of transformer oil during internal faults. The main t ask of this relay is to provide protection for low oil level and high temperature.
4. ***Core***. The core is made of laminated soft iron or steel that provides a low reluctance and continuous path to the flow of magnetic flux, and reduces eddy current loss and Hysteresis loss. Factors like voltage, current and frequency are considered before composing a transformer core. The diameter of this core is directly proportional to copper loss and inversely proportional to iron loss. Decrease in the diameter of the

core reduces the weight of steel used, which results in lesser core loss and increased copper loss. The exactly opposite occurs when the diameter is increased.

5. ***Windings***. Windings are several turns of copper coils bundled together; with each winding in the core insulated from the other. Windings are classified on the basis of the input and output supply, and the voltage range. There are two categories of windings present in a transformer – primary windings to which input voltage is applied, and secondary windings to which output voltage is applied.
6. ***Breather***. Due to the expansion and contraction of the insulating oil, moisture can arise which cause the pressure inside the conservator to change. This pressure is balanced by the flow of atmospheric air in and out of the conservator. If the moisture gets in touch with the insulating oil, it can affect the insulation and lead to internal faults. This makes it very important to keep the air entering the tank to be moisture-free. This is where the breather comes to the rescue, with its silica gel filling that absorbs all the moisture from the air that enters inside. Therefore, the breather acts like an air filter and controls the moisture levels inside the transformer.
7. ***Tap changer***. Tap changers are used to balance the voltage variations happening inside a transformer. These equipment are available as on-load or off-load. The on-load tap changers tapping can be changed without isolating the transformer from the supply, while the off-load tap changers tapping is done only after disconnecting the transformer.
8. ***Cooling Tubes***. As the name suggests, cooling tubes are used to cool the transformer oil. The transformer oil is either naturally or forcefully circulated through the cooling tubes to be cooled. In case of natural circulation, the temperature of the oil rises and the hot oil rises to the top while the cold oil sinks downward; while in case of forced circulation, an external pump is used for the same process.
9. ***Explosion vent***. In case of heavy internal faults, the boiling hot oil within the transformer needs to be expelled out to avoid explosion of the transformer. This is done through the explosion vent, which is placed at a level above the level of the conservator.
10. ***Thermometer***. Just like a normal thermometer, even the thermometer present in a transformer is used to measure the temperature. Used in transformers with value above 50KVA, the thermometer measure two temperatures – one of the oil, and second of the windings. In case of temperature rise above a safe level, the thermometer activates a signal or alarm.
11. ***High Voltage Bushing***. This is the terminals where the primary windings of the transformer terminates and serves as an insulator from the transformer tank. Its spacing is dependent on the voltage rating of the transformer.
12. ***Low Voltage Bushing*** – like the high voltage bushing, this is the terminals where the secondary windings of the transformer terminates and serves as an insulator from the transformer tank. Low voltage bushing can be easily distinguished from its high voltage counterpart since low voltage bushings are usually smaller in size compared to the high voltage bushing.
13. ***Cooling Fins/Radiator*** – in order for the transformer to dissipate the heat it generated in its oil-insulation, cooling fins and radiators are usually attached to the transformer tanks. The capacity of the transformer is dependent to its temperature

that is why it is imperative for it to have a cooling mechanism for better performance and higher efficiency.

14. ***Cooling Fans*** – can be usually found attached to the cooling fins. Cooling fans can be either be a timer controlled or a winding/oil temperature controlled. Cooling fans helps raises the transformer capacity during times when the temperature of the transformer rises due to its loading. Cooling fans used on the transformer are actuated by the help of a relaying device which when senses a relatively high temperature enables the fan to automatically run.
15. ***System Ground Terminal*** – system ground terminals in a power transformer are usually present whenever the connection type of the transformer windings has wye in it. This terminal can be found in-line with the main terminals of the transformer.
16. ***Drain Valve*** – can be usually found in the bottom part of the transformer tank. Drain valves are used whenever oil replacement is necessary. Through this valve, the replacement of oil in an oil-filled transformer can be easily done simply by opening this valve like that of a faucet.
17. ***Dehydrating Breather*** – Dehydrating breathers are used to prevent the normal moisture in the air from coming in contact with the oil in electrical equipment as the load or temperature changes. This reduces the degeneration of the oil and helps maintain its insulation capability. When used with conservator system with a rubber air cell it reduces moisture accumulation in the cell. Some breathers are designed for sealed tank transformers and breathe only at pre-set pressure levels.
18. ***Oil Temperature/Pressure gauges*** – these are used for monitoring the internal characteristics of the transformer especially its windings. These gauges help the operator in knowing the level of temperature and pressure inside the transformer (oil & winding). This will also serve as an alarm whenever a certain level is reached that could be harmful to the transformer windings.
19. ***Bushing Current Transformers*** – modern transformer construction today now includes current transformers. These are usually found around the transformer terminals which will be later be used for metering and relaying purposes. Its terminals are found in the control panels attached to the transformer.
20. ***Control Panel*** – this houses all of the transformer's monitoring devices terminals and auxiliary devices including the terminals of the bushing current transformers and cooling fans. Control panels are very useful especially when a remote control house is needed to be constructed, this will serve as their connection point.
21. ***Surge Arresters*** – this type of arresters are placed right directly before and after the transformer terminals in order to minimize the exposure of the transformer. Like any other surge arresters, its purpose is to clip sudden voltage surge that can be damaging to the winding of the transformer.

It is worthy to be noted that the maintenance of various items comprising a transformer is usually based on preventive maintenance schedules recommended by the manufacturer.

Chapter 3

Cooling Methods of Transformers

Objectives

This chapter presents various cooling methods of transformers. In addition, detailed comparisons between the fields of applications of various practical cooling systems are provided.

Transformer Losses and Dissipation Methods

As mentioned early in this chapter, transformer losses can be classified into core losses, and winding losses. The core losses are formed due to the hysteresis losses, and eddy current losses in the transformer ferromagnetic core. Various types of power losses are converted to heat energy. Heat is defined in physics as the transfer of thermal energy across a well-defined boundary around a thermodynamic system.

Generally, the heat from a source is transmitted to the surrounding through one or more of the heat transfer mechanisms. Heat transfer is a discipline of thermal engineering that concerns the generation, use, conversion, and exchange of thermal energy (heat) between physical systems. Heat transfer is classified into various mechanisms, such as ***conduction***, ***convection***, ***radiation***, ***and advection***.

1. ***Conduction (***also called ***diffusion)***.
   - The transfer of energy between objects that are in ***physical contact***. Thermal conductivity is the property of a material to conduct heat.
   - On a microscopic scale, heat conduction occurs as hot, rapidly moving or vibrating atoms and molecules interact with neighboring atoms and molecules, transferring some of their energy (heat) to these neighboring particles. In other words, heat is transferred by conduction when adjacent atoms vibrate against one another, or as electrons move from one atom to another. Conduction is the most significant means of heat transfer within a solid or between solid objects in thermal contact. Example: Heat transfer through metal rods.

2. ***Convection***.
   - Convective heat transfer, or convection, is the transfer of heat from one place to another by the ***movement of fluids***, a process that is essentially the transfer of heat via mass transfer.
   - Bulk motion of fluid enhances heat transfer in many physical situations, such as (for example) between a solid surface and the fluid. Convection is usually the dominant form of heat transfer in liquids and gases.

- The flow of fluid may be forced by external processes, or sometimes (in gravitational fields) by buoyancy forces caused when thermal energy expands the fluid (for example in a fire plume), thus influencing its own transfer. The latter process is often called "natural convection". All convective processes also move heat partly by diffusion, as well. Another form of convection is forced convection. In this case the fluid is forced to flow by using a pump, fan or other mechanical means.
- Convective cooling is sometimes described as *Newton's law of cooling*: "*The rate of heat loss of a body is proportional to the temperature difference between the body and its surroundings*"; however, by definition, the validity of Newton's law of Cooling requires that the rate of heat loss from convection be a linear function of ("proportional to") the temperature difference that drives heat transfer, and in convective cooling this is sometimes not the case. In general, convection is not linearly dependent on temperature gradients, and in some cases is strongly nonlinear. In these cases, Newton's law does not apply.

3. ***Radiation***.
   - Thermal radiation is energy emitted by matter as ***electromagnetic waves***, due to the pool of thermal energy in all matter with a temperature above absolute zero. Thermal radiation propagates without the presence of matter through the vacuum of space.
   - Thermal radiation occurs through a vacuum or any transparent medium (solid or fluid or gas). It is the transfer of energy by means of photons in electromagnetic waves governed by the same laws.
   - Thermal radiation is a direct result of the random movements of atoms and molecules in matter. Since these atoms and molecules are composed of charged particles (protons and electrons), their movement results in the emission of electromagnetic radiation, which carries energy away from the surface.

4. ***Advection***.
   - Advection is the transport mechanism of a fluid from one location to another, and is dependent on motion and momentum of that fluid.
   - By ***transferring matter***, energy—including thermal energy—is moved by the physical transfer of a hot or cold object from one place to another.This can be as simple as placing hot water in a bottle and heating a bed, or the movement of an iceberg in changing ocean currents. A practical example is thermal hydraulics.

Transformer Cooling

The transformer's output power is generally less than its input power. The difference is the amount of power converted into heat by core loss and winding losses. The losses and the heat dissipation increases with increase in the capacity of the transformer.

If the heat losses generated within a transformer 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. In addition, the heat rise causes significant reduction in the lifetime of the insulation of various electrical equipment including transformers. It is a rule of thumb that the life expectancy of electrical insulation is halved for about every 7°C to 10°C increase in operating temperature. Therefore, it is essential to control the temperature with in 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 many cooling methods available for transformers.

Cooling of a transformer is the process of dissipation of heat developed in the transformer to the surroundings. The losses occurring in the transformer are converted into heat which increases the temperature of the windings and the core. In order to dissipate the heat generated cooling should be done. There are two ways of cooling the transformer:

- First, *the coolant circulating inside the transformer transfers the heat from the windings and the core entirely to the tank walls and then it is dissipated to the surrounding medium.*
- Second, *along with the first technique, the heat can also be transferred by coolants inside the transformer.*

The choice of the cooling method used depends on the size, type of applications and the working conditions.

The coolants used in the transformer are ***air*** and ***oil***. In ***dry-type transformers***, air coolant is used, while in ***oil-immersed transformers***, oil is user. These coolants also act as electrical insulators. In the first said, the heat generated is conducted across the core and windings and then dissipated from the outer surface of the core and windings to the surrounding air. In the next, heat is transferred to the oil surrounding the core and windings and it is conducted to the walls of the transformer tank. Finally the heat is transferred to the surround air by radiation and convection.

Generally, there three cooling methods available for transformers; ***air cooling***, ***oil and air cooling***, and ***oil and water cooling***. The first method is used in dry-type transformers, while the later methods are used in oil-immersed transformers. In all situations, the cooling can be performed through natural flow or forced flow of the coolant(s). In the oil-based cooling method, the heat is transferred to the oil surrounding the core and windings and it is conducted to the walls of the transformer tank. Finally, the heat is transferred to the surrounding air by radiation and convection. The oil as a coolant has two distinct advantages over the air coolants:

- It provides better conduction than the air, and
- High coefficient of conduction, which results in the natural circulation of the oil.

The cooling method is selected as follows:

- For dry-type transformers
  - Air Natural(AN) also called Self Air Cooled Transformers
  - Air Blast (AB)
- For oil-immersed transformers of capacity ≤ 30 MVA
  - Oil Natural - Air Natural (ONAN)
  - Oil Natural - Air Forced (ONAF)
  - Oil Forced - Air Natural (OFAN)
  - Oil Forced - Air Forced (OFAF)
- For oil-immersed transformers of capacity > 30 MVA
  - Oil Natural - Water Forced (ONWF)
  - Oil Forced - Water Forced (OFWF)

Air Natural (AN) Cooling of Dry-type Transformers

The construction of an air natural cooling of dry-type power transformer is shown in Fig. 1. This method of transformer cooling is generally used in small transformers (upto 3 MVA). In this method the transformer is allowed to cool by natural air flow surrounding it.

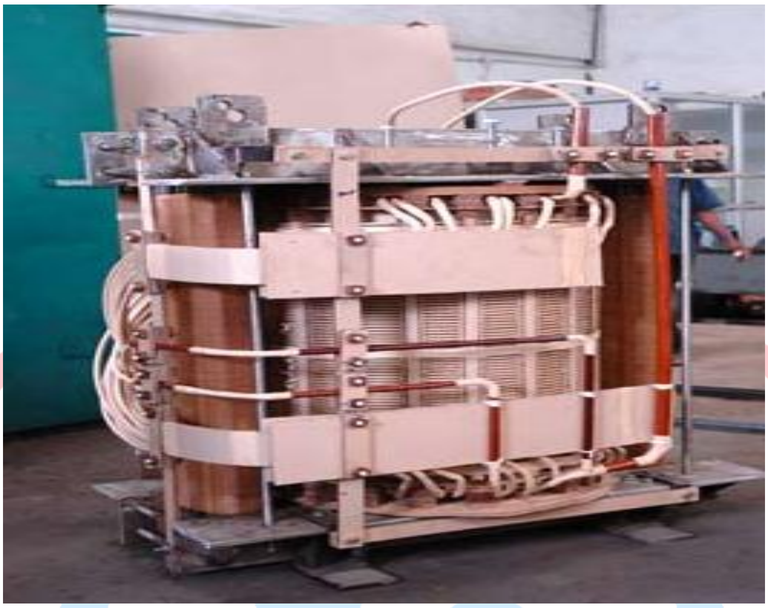


Fig. 1: Dry-type transformer with

The AN cooling method uses the ambient air as the cooling medium. *The natural circulation of the air is used for dissipation of heat generated by natural convection*. The core and the windings are protected from mechanical damage by providing a metal enclosure. This method is suitable for transformers of rating up to 1.5 MVA. This method is adopted in the places where fire is a great hazard.

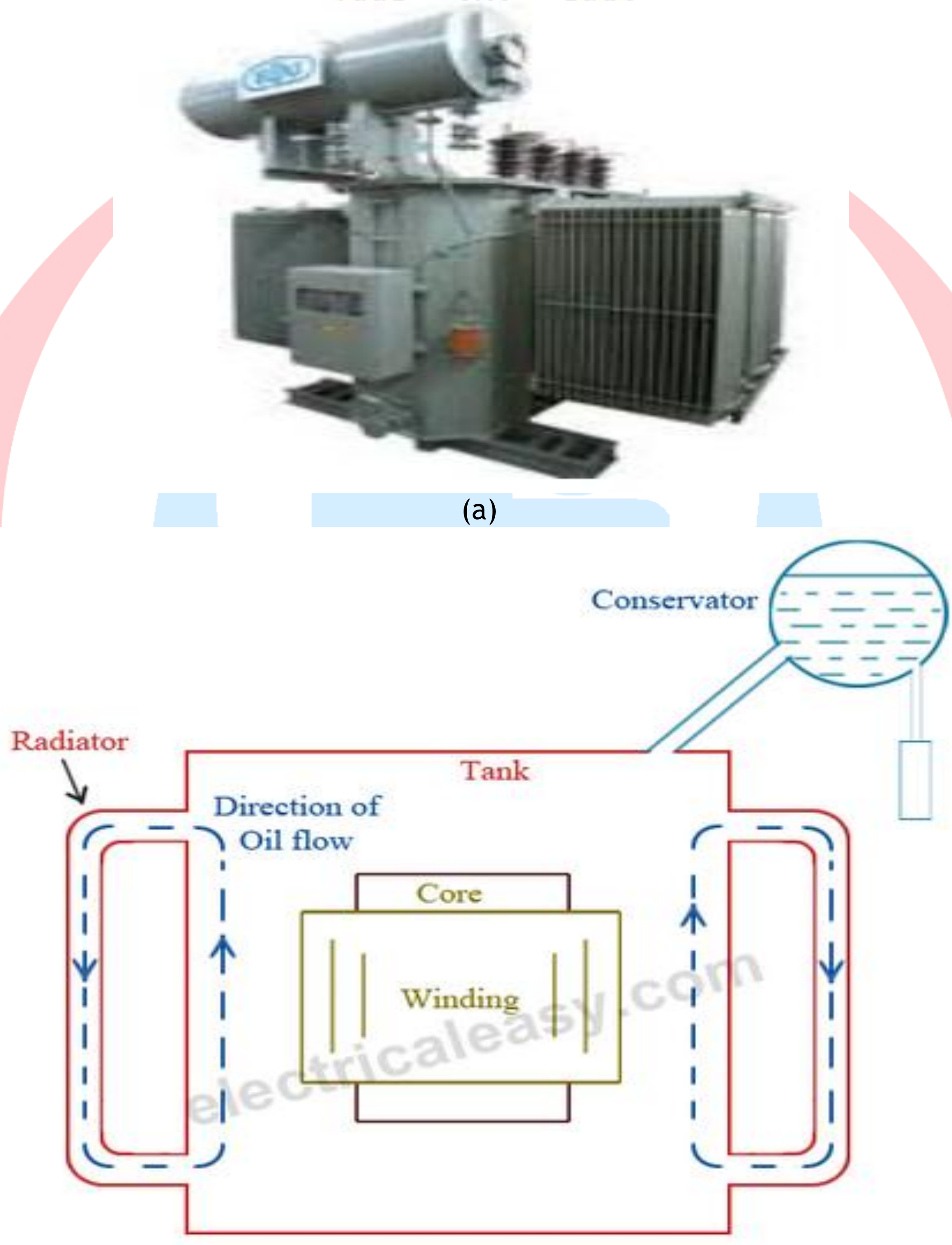
Air Blast (AB) Cooling of Dry-type Transformers

For transformers rated more than 3 MVA, cooling by natural air method is inadequate. In such cases, the air is forced on the core and windings with the help of fans or blowers (see Fig. 2). The air supply must be filtered to prevent the accumulation of dust particles in ventilation ducts. This method can be used for transformers up to 15 MVA.

Fig. 2: Air fan used in the air blast (AB) cooling of dry-type transformers

Oil Natural - Air Natural (ONAN) Cooling

This method is used for oil immersed transformers. In this method, the heat generated in the core and winding is transferred to the oil. According to the principle of convection, the heated oil flows in the upward direction and then in the radiator; see Fig. 3. The vacant place is filled up by cooled oil from the radiator. The heat from the oil will dissipate in the atmosphere due to the natural air flow around the transformer. In this way, the oil in transformer keeps circulating due to natural convection and dissipating heat in atmosphere due to natural conduction. This method can be used for transformers up to about 30 MVA.



(b)

Fig. 3: ONAN cooling of oil-immersed transformers. (a) Transformer structure; (b) Natural flow of the heated oil.

Oil Natural - Air Forced (ONAF) Cooling

The heat dissipation can be improved further by applying forced air on the dissipating surface. Forced air provides faster heat dissipation than natural air flow. In this method, fans are mounted near the radiator and may be provided with an automatic starting arrangement, which turns on when temperature increases beyond certain value; Fig. 4. This transformer cooling method is generally used for large transformers up to about 60 MVA.

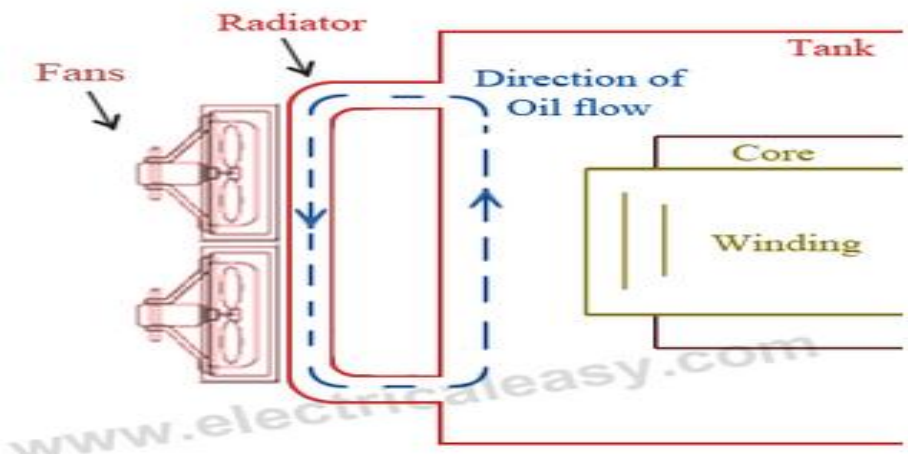
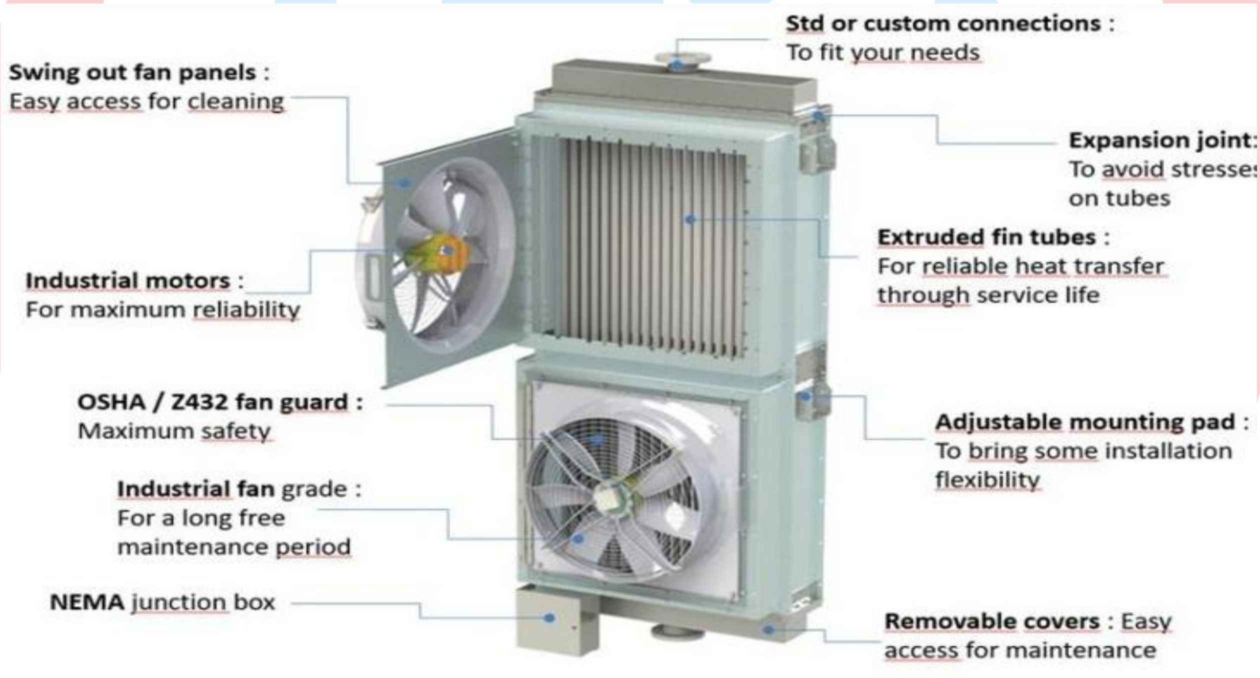
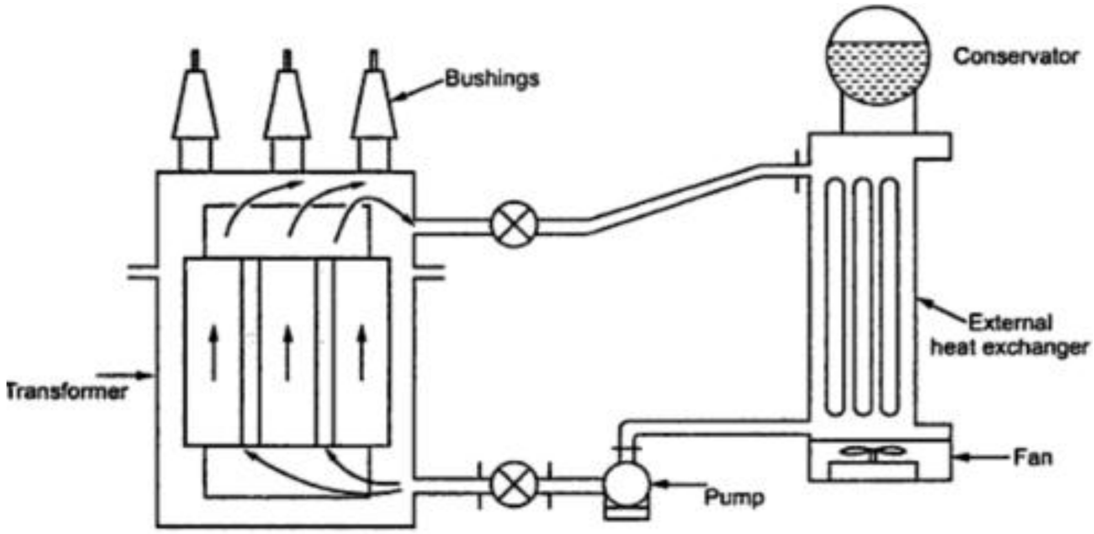


Fig. 4: ONAF cooling of oil-immersed transformers

Oil Forced - Air Forced (OFAF) Cooling



(a)



(b)

Fig. 5: OFAF cooling of oil-immersed transformers

In this method as shown in Fig. 5, oil is circulated with the help of a pump. The oil circulation is forced through the heat exchangers. Compressed air is also forced to flow on the heat exchanger with the help of fans. The heat exchangers may be mounted separately from the transformer tank and connected through pipes at top and bottom as shown in the figure. This type of cooling is provided for higher rating transformers at substations or power stations.

Oil Forced - Water Forced (OFWF) Cooling

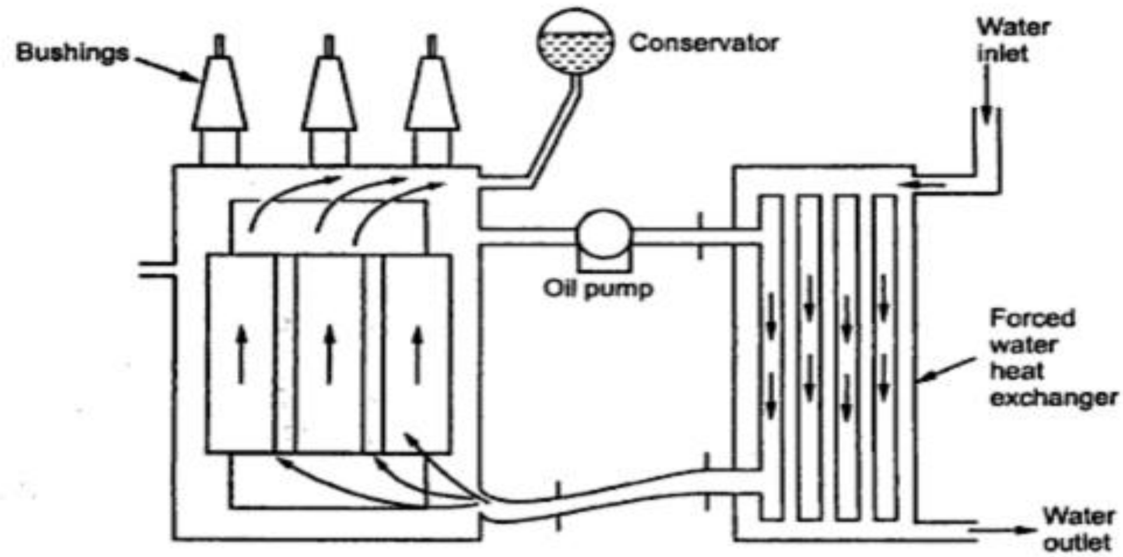


Fig. 6: OFWF cooling of oil-immersed transformers

This method is similar to OFAF method, but here forced water flow is used to dissipate hear from the heat exchangers as shown in Fig. 6. The oil is forced to flow through the heat exchanger with the help of a pump, where the heat is dissipated in the water which is also forced to flow. The heated water is taken away to cool in separate coolers. This type of cooling is used in very large transformers having rating of several hundred MVA.

Chapter 4

Current and Voltage Sensing (Instrument) Transformers

Objectives

This chapter presents the basics of instrument transformers, their structures, and their applications.

Introduction

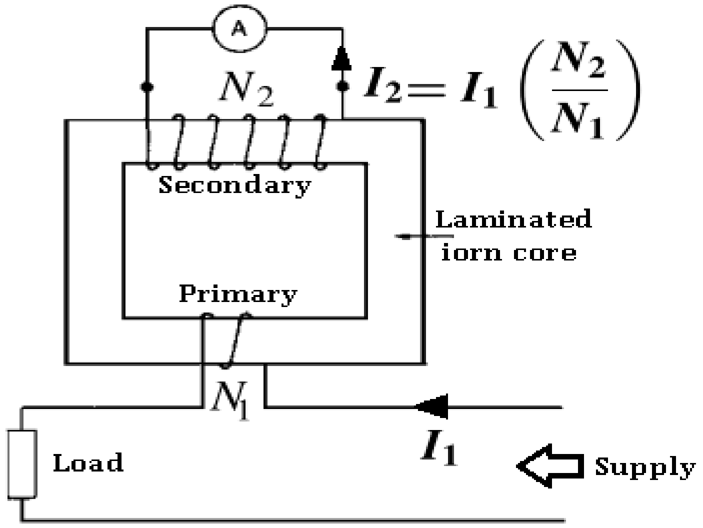
Instrument transformers *transform currents, or voltages from usually high values to lower values suitable for feeding relays, control circuits, and measuring instruments. Like the power transformers, they provide a magnetic non-electrical coupling between their primary electrical circuit, and their secondary electrical circuits. Therefore, the secondary circuit of an instrument transformer (low power circuit for protection, or control, or measurements) is electrical isolated from the high power circuit of the primary side of the transformers*. From functionality point of view, instrument transformers are classified to ***current 'sensing' instrument transformers***, and ***voltage 'sensing' instrument transformers***.

An ***isolating transformer*** *is a special type of instrument transformers with turns ratio of 1:1*. Isolating transformers are used in several important applications, including bathroom shaver-sockets, portable electric tools, model railways … etc. It is worthy to be noted that the *instrument transformers and the power transformers have the same operating principles, and common laws of performance*.

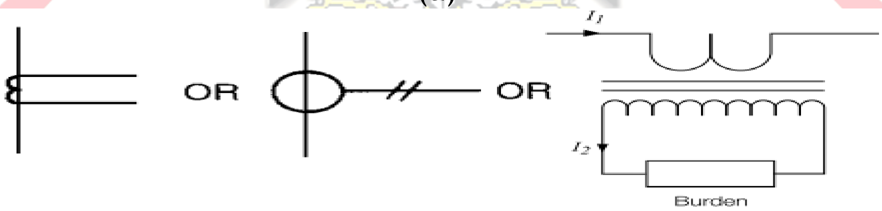
Current Transformers (CTs)

A ***Current Transformer*** (CT) is a type of "instrument transformer" that is designed to produce an alternating current in its secondary winding which is proportional to the current being measured in its primary. Current transformers reduce high-voltage currents to a much lower value and provide a convenient way of safely monitoring the actual electrical current flowing in an AC transmission line using a standard ammeter. The principal of operation of a basic current transformer is slightly different from that of an ordinary power or voltage transformer.

Unlike the voltage or power transformer looked at the previous chapters, the current transformer consists of only one or very few turns as its primary winding as shown in Fig. 1(a), while the circuit symbols of current transformers are shown in Fig. 1(b). This primary winding can be of either a single flat turn, a coil of heavy duty wire wrapped around the core or just a conductor or bus bar placed through a central hole as shown in Fig. 1(c).



(a)



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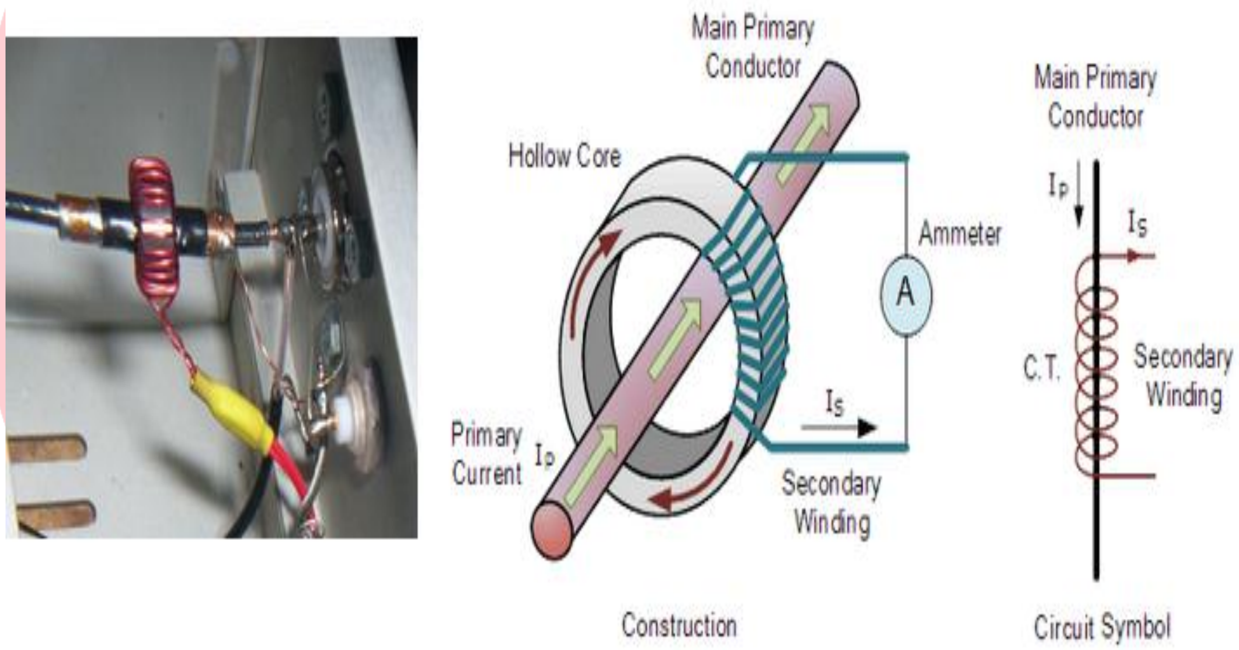


(c)

Fig. 1: Current transformers. (a) Operating principles; (b) Symbols; (c) Physical construction and connection

In three-phase systems, each phase is equipped with a separate CT for sensing the current of each phase as shown in Fig. 2.

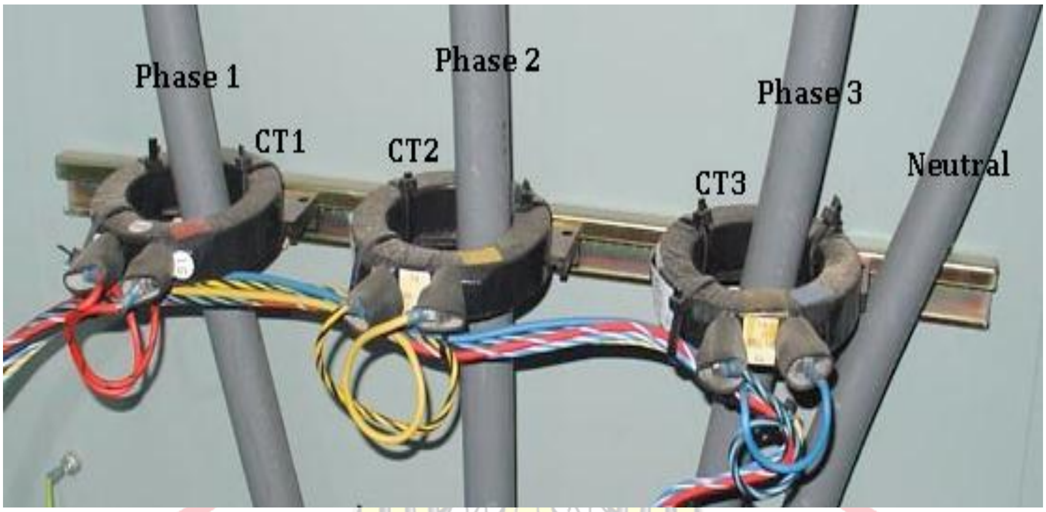
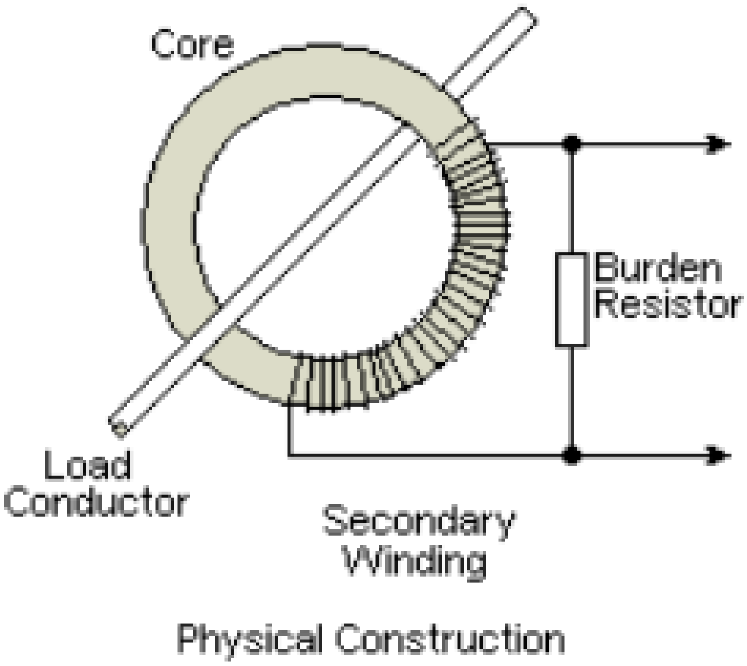
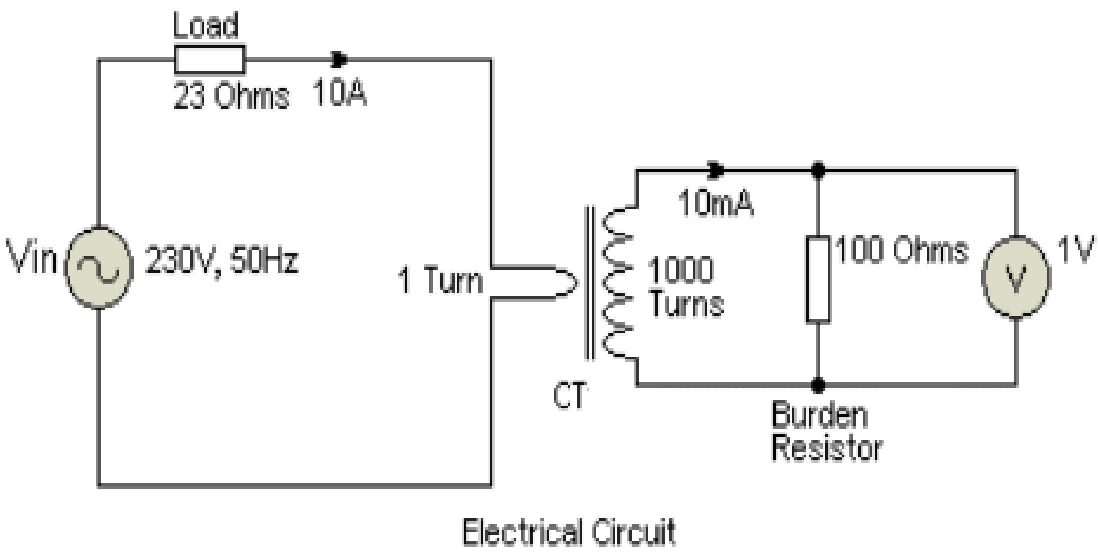


Fig. 2: Three-phase systems with CTs

Due to this type of arrangement, the current transformer is often referred to as a "***series transformer***" as the primary winding, which never has more than a very few turns (Fig. 1), is in series with the current carrying conductor supplying a load. On the other hand, the secondary winding may have a large number of coil turns wound on a laminated core of low-loss magnetic material. This core has a large cross-sectional area so that the magnetic flux density created is low using much smaller cross-sectional area wire, depending upon how much the current must be stepped down as it tries to output a constant current, independent of the connected load. The secondary winding will supply a current into either a short circuit, in the form of an ammeter, or into a resistive load (burden resistor) as shown in example of Fig. 3 until the voltage induced in the secondary is big enough to saturate the core or cause failure from excessive voltage breakdown. Unlike a voltage transformer, the primary current of a current transformer is not dependent of the secondary load current, but instead is controlled by an external load. The secondary current is usually rated at a standard 1 Ampere or 5 Amperes for larger primary current ratings.



(a)



(b)

Fig. 3: Use of burden resistor with CTs. (a) Physical construction; (b) Electrical circuit

There are three basic types of current transformers: wound, toroidal, and bar.

- ***Wound Current Transformer*** (Fig. 4) – The transformers primary winding is physically connected in series with the conductor that carries the measured current flowing in the circuit. The magnitude of the secondary current is dependent on the turns ratio of the transformer.

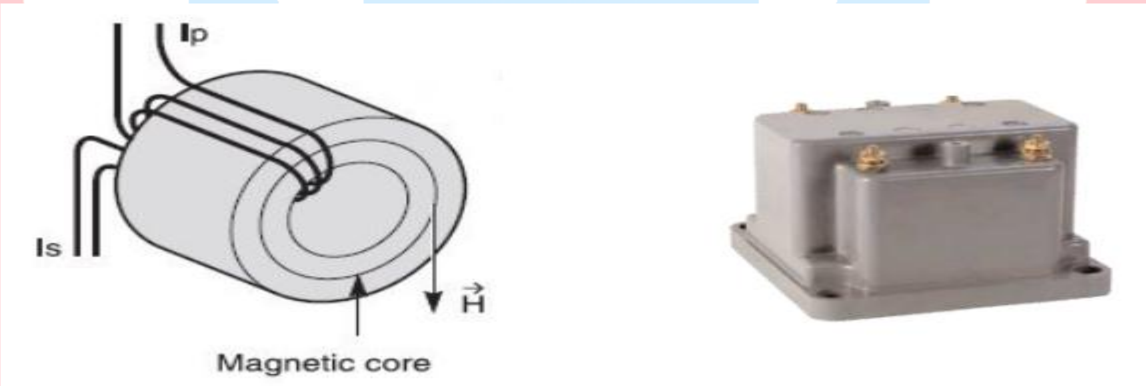
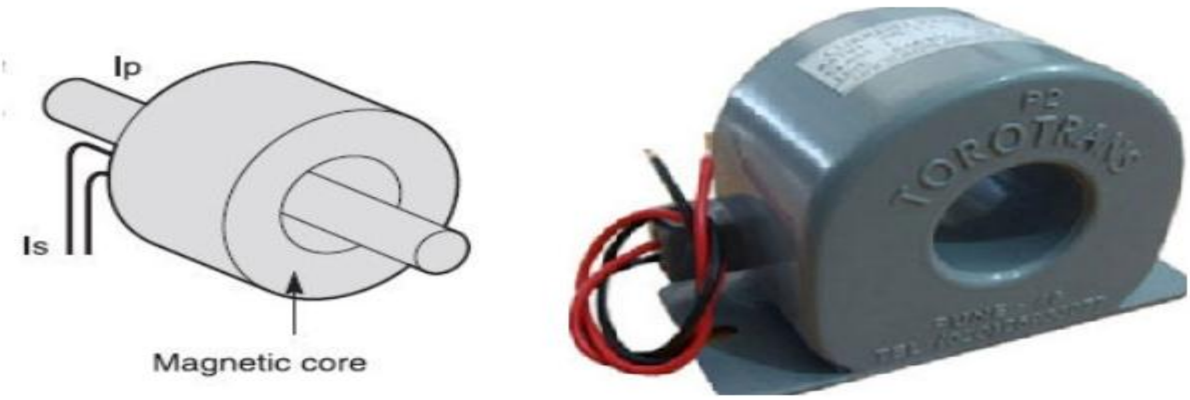


Fig. 4: Wound type CT



(a)

(b)

Fig. 5: Toroidal Current Transformer. (a) Closed core; (b) Open or split core

- ***Toroidal Current Transformer*** – These CTs do not contain a primary winding as shown in Fig. 5. Instead, the line that carries the current flowing in the network is threaded through a window or hole in the toroidal transformer. Some current transformers have a "***split core***" which allows it to be opened, installed, and closed, without disconnecting the circuit to which they are attached.
- ***Bar-type Current Transformer*** – This type of current transformer uses the actual cable or bus-bar of the main circuit as the primary winding, which is equivalent to a single turn; Fig. 6. They are fully insulated from the high operating voltage of the system and are usually bolted to the current carrying device.

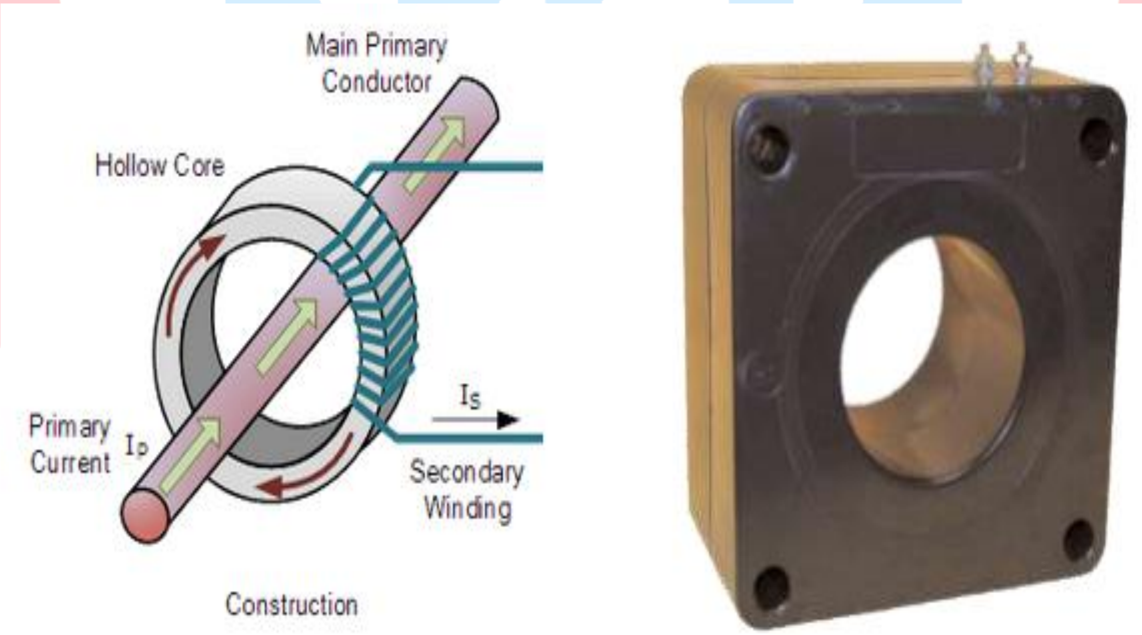


Fig. 6: Bar-type CT

Example 1

A current transformer has a single turn on the primary winding and a secondary winding of 60 turns. The secondary winding is connected to an ammeter with a resistance of 0.15 Ω. The resistance of the secondary winding is 0.25 Ω. If the current in the primary winding is 300 A, determine:

a) The reading on the ammeter,
b) The potential difference across the ammeter, and
c) The total load (in VA) on the secondary.

Solution

(a) Reading on the ammeter,

$$I_2 = I_1 \left(\frac{N_1}{N_2}\right) = 300\left(\frac{1}{60}\right) = \mathbf{5\,A}.$$

(b) P.d. across the ammeter $= I_2 R_A$, (where R_A is the ammeter resistance) $= (5)(0.15) = \mathbf{0.75\ volts}$.

(c) Total resistance of secondary circuit $= 0.15 + 0.25 = 0.40\,\Omega$.
Induced e.m.f. in secondary $= (5)(0.40) = 2.0\,V$.
Total load on secondary $= (2.0)(5) = \mathbf{10\,VA}$.

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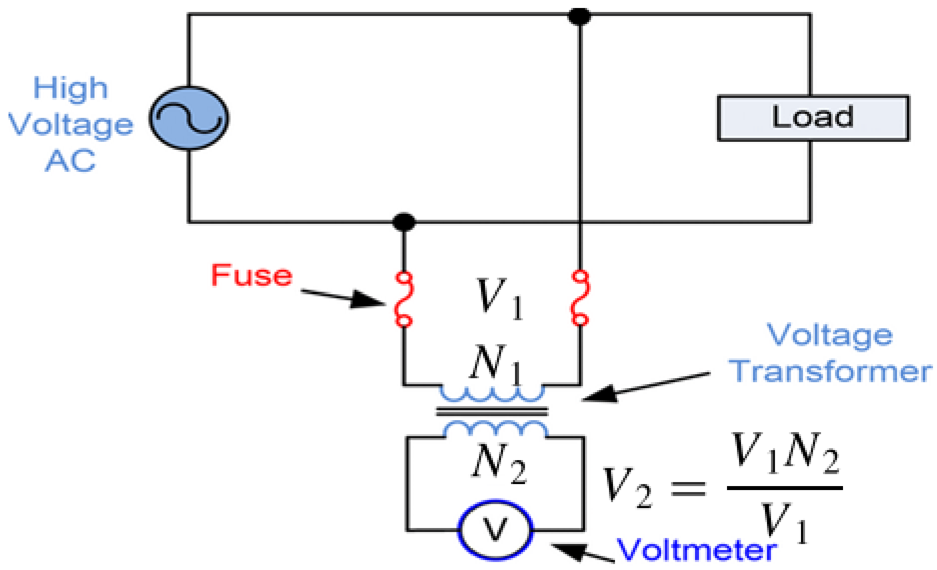
Potential Transformer (VT) or Potential Transformers (PTs)

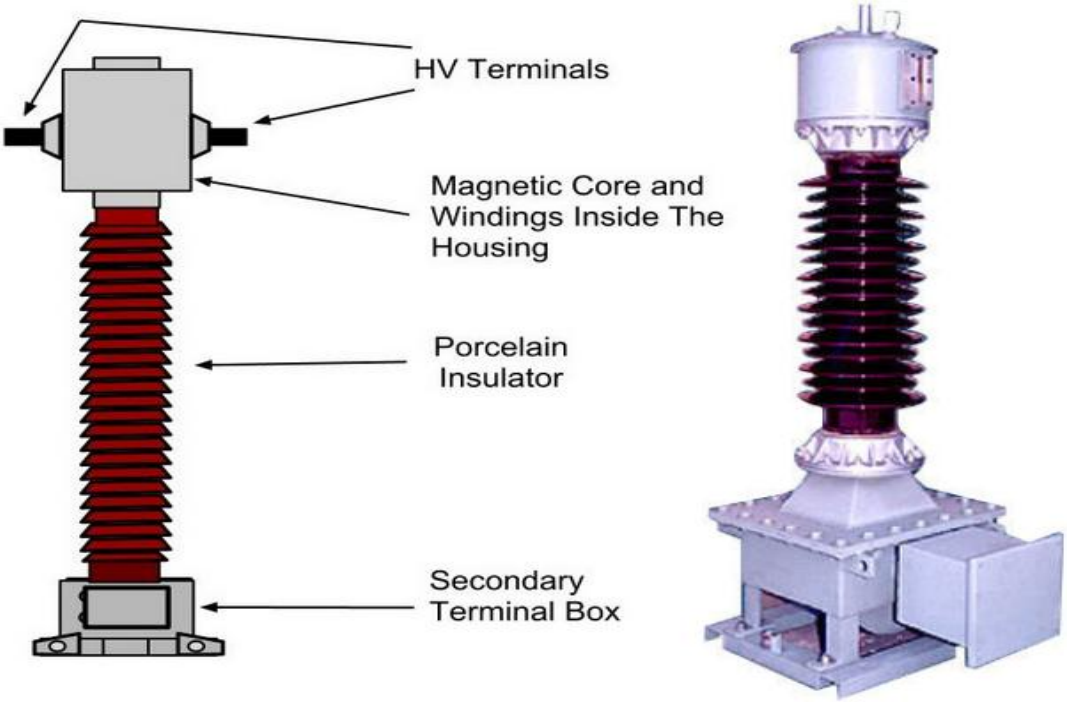
Voltage transformers (VT), also called potential transformers (PT), are a parallel connected type of instrument transformer; Fig. 7. They are designed to present negligible load to the supply being measured and have an accurate voltage ratio and phase relationship to enable accurate secondary connected metering. The PT is typically described by its voltage ratio from primary to secondary. For example, a 600:120 PT will provide an output voltage of 120 volts when 600 volts are impressed across its primary winding. Standard secondary voltage ratings are 120 volts and 70 volts, compatible with standard measuring instruments. For high voltage and extra high voltage grid applications, Fig. 8 shows the structure of PTs in single phase, and three phases.



(a)

(b)

Fig. 7: Potential transformer. (a) Circuit connection; (b) Low and medium voltage PTs



(a)

(b)

Fig. 8: PTs used in high voltage and extra high systems. (a) Single phase; (b) Three phases

There are three main types of potential transformers (PT): *electromagnetic*, *capacitor*, and *optical*.

- ***Electromagnetic potential transformer*** is a wire-wound transformer. It has a similar structure as the power transformer presented in the previous chapter.
- ***The capacitor voltage transformer*** (CVT) shown in Fig. 9 uses a capacitance potential divider and is used at higher voltages due to a lower cost than an electromagnetic PT.

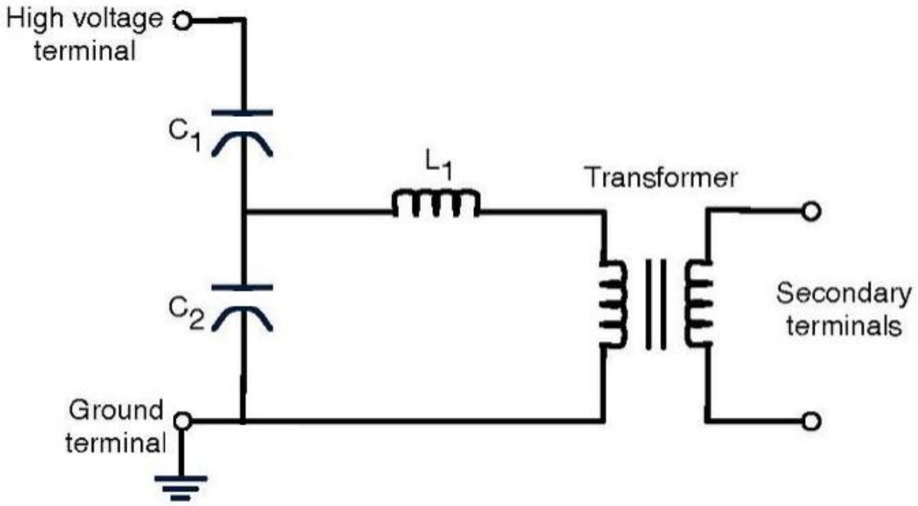


Fig.9: Capacitive PT

- ***Optical voltage transformer*** (Fig. 10) exploits the Faraday effect[2], rotating polarized light, in optical materials

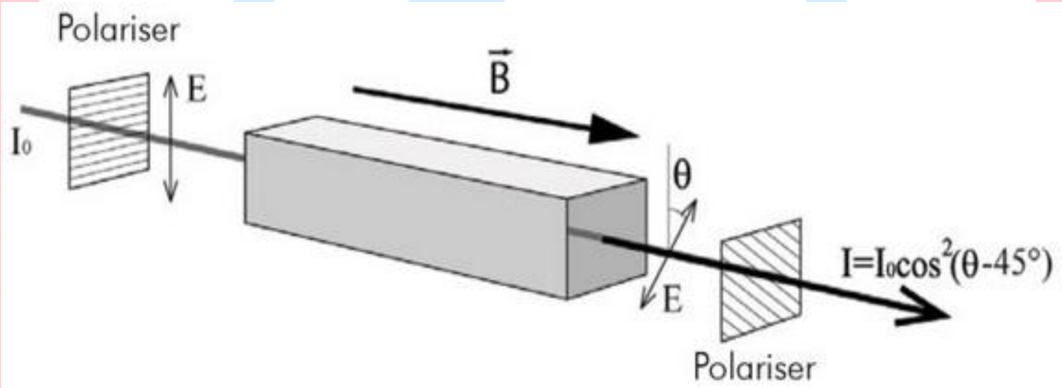


Fig. 10: Optical PT

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[2] *In physics, the Faraday effect or Faraday rotation is a magneto-optical phenomenon—that is, an interaction between light and a magnetic field in a medium. The Faraday effect causes a rotation of the plane of polarization which is linearly proportional to the component of the magnetic field in the direction of propagation. Formally, it is a special case of gyroelectromagnetism obtained when the dielectric permittivity tensor is diagonal.*

References

[5] Bird J. Electrical and electronic principles and technology. Routledge; 2010.
[6] Harlow JH. Electric power transformer engineering. CRC press; 2012.
[7] Bakshi KB. Electrical Measurements & Measuring Instruments. Technical Publications; 2007.
[8] John J, Winders J. Power Transformers Principles and Applications. New York. 2002.
[9] Gönen T. Electric power distribution system engineering. New York: McGraw-Hill; 1986.

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