I Year - II Semester	L	T	P	C
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BASIC ELECTRICAL AND ELECTRONICS ENGINEERING

Preamble:

This course covers the topics related to analysis of various electrical circuits, operation of various electrical machines, various electronic components to perform well in their respective fields.

Learning Objectives:

- To learn the basic principles of electrical circuital law's and analysis of networks.
- To understand the principle of operation and construction details of DC machines & Transformers.
- To understand the principle of operation and construction details of alternator and 3-Phase induction motor.
- To study the operation of PN junction diode, half wave, full wave rectifiers and OP-AMPs.
- To learn the operation of PNP and NPN transistors and various amplifiers.

UNIT - I

Electrical Circuits:

Basic definitions - Types of network elements - Ohm's Law - Kirchhoff's Laws - Inductive networks - Capacitive networks – Series - Parallel circuits - Star-delta and delta-star transformations.

UNIT - II

Dc Machines:

Principle of operation of DC generator – EMF equation - Types of DC machine – Torque equation – Applications – Three point starter - Speed control methods of DC motor – Swinburne's Test.

UNIT - III

Transformers:

Principle of operation and construction of single phase transformers – EMF equation – Losses – OC & SC tests - Efficiency and regulation.

UNIT - IV

AC Rotating Machines:

Principle of operation and construction of alternators– Types of alternators – Principle of operation of synchronous motor - Principle of operation of 3-Phase induction motor – Slip-torque characteristics - Efficiency – Applications.

UNIT V

Rectifiers & Linear ICs:

PN junction diodes - Diode applications(Half wave and bridge rectifiers). Characteristics of operation amplifiers (OP-AMP) - application of OP-AMPs (inverting, non-inverting, integrator and differentiator).

UNIT VI

Transistors:

PNP and NPN junction transistor, transistor as an amplifier- Transistor amplifier - Frequency response of CE amplifier - Concepts of feedback amplifier.

Learning Outcomes:

- Able to analyse the various electrical networks.
- Able to understand the operation of DC generators,3-point starter and DC machine testing by Swinburne's Test.
- Able to analyse the performance of single-phase transformer.
- Able to explain the operation of 3-phase alternator and 3-phase induction motors.
- Able to analyse the operation of half wave, full wave bridge rectifiers and OP-AMPs.
- Able to explain the single stage CE amplifier and concept of feedback amplifier.

Text Books:

1. Electrical Technology by Surinder Pal Bali, Pearson Publications.

2. Electronic Devices and Circuits, R.L. Boylestad and Louis Nashelsky, 9th edition, PEI/PHI 2006.

Reference Books:

1.Electrical Circuit Theory and Technology by John Bird, Routledge Taylor &Francis Group

2. Basic Electrical Engineering by M.S.Naidu and S.Kamakshiah,TMH Publications

3.Fundamentals of Electrical Engineering by Rajendra Prasad, PHI Publications,2nd edition

4.Basic Electrical Engineering by Nagsarkar,Sukhija, Oxford Publications,2nd edition

5.Industrial Electronics by G.K. Mittal, PHI

Unit-I

Electrical Circuits

Introduction

1. Electric charge(Q)

In all atoms there exists number of electrons which are very loosely bounded to its nucleus. Such electrons are free to wander when specific forces are applied. If any of these electrons is removed, the atom becomes positively charged. And if excess electrons are added to the atom it becomes positively charged.

The total deficiency or addition of electrons in an atom is called its charge. A charged atom is called **Ion**. An element containing a number of ionized atoms is said to be charged. And accordingly the element consisting of that atom is said to be positively or negatively charged.

Particle	Electric charge possessed by particle of one number (C)	Atomic charge
Protons	$+1.6022X\ 10^{-19}$	+1
Neutrons	0	0
Electrons	$1.6022X\ 10^{-19}$	-1

The unit of measurement of charge is **Coulomb** (C). It can be defined as the charge possessed by number of electrons.

Hence if an element has a positive charge of one coulomb then that element has a deficiency of number of electrons.

<u>Conductors:</u>

The atoms of different materials differ in the number of electrons, protons and neutrons, which they contain. They also differ in how tightly the electrons in the outer orbit are bound to the nucleus. The electrons, which are loosely bound to their nuclei, are called **free electrons.** These free electrons may be dislodged from an atom by giving them additional energy. Thus they may be transferred from one atom to another. The electrical properties of materials largely depend upon the number of free electrons available.

A **conductor** is a material in which large number of free electrons is available. Thus current can flow easily through a conductor. All materials with resistivity less than 10^{-3} Ωm come under the category of conductors. Almost all metals are conductors.

Silver, copper Aluminum, carbon is some examples of conductors. Copper and Aluminum conductors are widely used in practice.

Insulators

Insulators are materials in which the outer electrons are tightly bound to the nucleus. It is very difficult to take out the electrons from their orbits. Consequently, current cannot flow through them. All materials with resistivity above 10^5 Ωm fall in the category of insulators.

Examples of insulators are mica, paper, glass, porcelain, rubber, oil and plastics.

Semiconductors

In some materials, the electrons in the outer orbits are normally held by the nucleus, but can be taken out by some means. These materials are called **semiconductors.**

Materials such as germanium and silicon are examples of semiconductors. The addition of slight traces of impurity to silicon or germanium can free the electrons. The semiconductors have resistivity between 10^{-3} and 10^5 Ωm.

Current(I)

An electric current is the movement of electric charges along a definite path. In case of a conductor the moving charges are electrons.

The unit of current in the International system of Units is the ***ampere (A)***.

The ampere is defined as that current which when flowing in two infinitely long parallel conductors of negligible cross-section, situated 1 meter apart in vacuum, produces between the conductors a force of 2×10^{-7} Newton per meter length.

Voltage(V)

Energy is required for the movement of charge from one point to another. Let W joules of energy be required to move positive charge of Q coulombs from *a* point a to *b* in a circuit. We say that a voltage exists between the two points.

The voltage across two terminals is a measure of the work required to move charge through the element. The unit of voltage is the volt, and 1 volt is the same as 1 J/C. Voltage is represented by V or *v*.

The voltage V between two points may be defined in terms of energy that would be required if a charge were transferred from one point to the other. A voltage can exist between the two electrical terminals whether a current is flowing or not.

Voltage between *a* and *b* is given by

$$\boxed{V = \frac{W}{Q}\ (J/C)}$$

Electromotive Force (EMF)

The emf represents the driving influence that causes a current to flow, and may be interpreted to represent the energy that is used during passing of a unit charge through the source. The term emf is always associated with energy conversion. The emf is usually represented by the symbol E and has the unit **VOLT**

If W = energy imparted by the voltage source in joules (J)
Q = charge transferred through the source in coulombs ©
E = e.m.f. of the source

Then

$$\boxed{E = \frac{W}{Q}(J/C)}$$

Potential Difference:

The potential difference (p.d.) between two points is the energy required to move one coulomb of charge from one to the other.

If : W = energy required to transfer the charge
Q = charge transferred between the points
V = potential difference

Then

$$\boxed{V = \frac{W}{Q}(J / C)}$$

Electric Power

Power is the rate at which work is done. Work is done whenever a force causes motion. If a mechanical force is applied to lift or move a weight, work is done. We know that voltage is an electric force and it forces current to flow in a circuit. When voltage causes current flow (electrons to move), work is done.

The rate at which is work is done is called electric power and is measured in **watts**.

$$\boxed{P = \frac{W}{t}(J / s)}$$

Basic Circuit Components

Resistor, inductor, and capacitor are the three basic components of a network. A resistor is an element that dissipates energy as heat when current passes through it. An inductor stores energy by virtue of a current through it. A capacitor stores energy by virtue of a voltage existing across it.

Resistance

The opposition offered by a substance to the flow of electric current is called **resistance**. Since current is the flow of free electrons, resistance is the opposition offered by the substance to flow of free electrons. This opposition occurs because atoms and molecules of the substance obstruct the flow of these electrons. Certain substances (e.g., metals such as silver, copper, aluminum etc) offer very little opposition to the flow of electric current and are called conductors. On the other hand, those substances which offer high opposition to the flow of electric current (i.e., flow of free electrons) are called insulators e.g., glass, rubber, mica, dry wood etc.

It may be noted here that resistance is the electric friction offered by the substance and causes production of heat with the flow of electric current. The moving electrons collide with atoms or molecules of the substance ; each collision resulting in the liberation of minute quantity of heat.

- Denoted by **R**
- Unit is **Ohms(Ω)**
- Symbol :

Unit of resistance: The practical unit of resistance is ohm and is represented by the symbol Ω. It is defined as under:
A wire is said to have a resistance of **1 ohm** *if a p.d. of 1 volt across its ends causes 1 ampere of current to flow through it.*

Factors upon which Resistance Depends:

The resistance R of a conductor
(i) is directly proportional to its length (l)
(ii) is inversely proportional to its area of cross-section (a)
(iii) Depends upon the nature of material.
(iv) Changes with temperature.

From the first three points (leaving temperature for the time being), we have,

$$\boxed{R \propto \frac{l}{a}} \quad \text{or} \quad \boxed{R = \rho \frac{l}{a}}$$

Where ρ (Greek letter 'Rho') is a constant and is known as resistivity or specific resistance of the material. Its value depends upon the nature of material.

Material	Resistivity ρ (ohm m)
Copper	$1.68x10^{-8}$
Aluminum	$2.65x10^{-8}$
Tungsten	$5.60x10^{-8}$

Conductance:

Conductance (G) is the reciprocal of resistance.

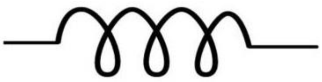
We know $$\boxed{G = \frac{1}{R} = \frac{1}{\rho}\frac{A}{l}} \ \textbf{or} \ \boxed{G = \sigma \frac{A}{l}}$$

Where σ (Greek letter 'sigma') is called the conductivity or specific conductance of the material. The unit of conductance is mho.

Inductors

The electrical element that stores energy in association with a flow of current is called *inductor* . The idealized circuit model for the inductor is called an *inductance.* Practical inductors are made of many turns of thin wire wound on a magnetic core or an air core. A unique feature of the inductance is that its presence in a circuit is felt only when there is a changing current. Fig below shows a schematic representation of an inductor.

- Denoted as L.
- Units: Henry (H).
- Symbol



Schematic representation of an inductor

For the ideal circuit model of an inductor, the voltage across it is proportional to the rate of change of current in it. Thus if the rate of change of current is di/dt and *v* is the induced voltage, then

$$\boxed{v \;\; \alpha \;\; \frac{di}{dt}} \quad \text{or} \quad \boxed{v = \text{L}\ \frac{di}{dt}}\ \text{volt} \qquad \text{(Eq – 1)}$$

In the above equation proportionality constant L is called inductance. The unit of inductance is Henry, named after the American physicist Joseph Henry. Equation may be rewritten as

$$\boxed{\text{L} = \frac{v}{\frac{di}{dt}} = \frac{volt - \sec ond}{ampere}} \quad \text{or} \quad \text{Henrys (H)} \qquad \text{(Eq – 2)}$$

If an inductor induces a voltage of 1 V when the current is uniformly varying at the rate of 1 A/sec, it is said to have an inductance of 1 H. Integrating Eq – 1 with respect to time t,

$$\boxed{i = \frac{1}{L}\int_0^t vdt + i(0)} \qquad \text{(Eq –3)}$$

Where $i(0)$ is the current at t = 0. From Eq – 3 it may be inferred that the current in an inductor cannot change suddenly in zero time.

Instantaneous power *p* entering the inductor at any instant is given by

$$\boxed{p = vi = Li\frac{di}{dt}} \qquad \text{(Eq – 4)}$$

When the current is constant, the derivative is zero and no additional energy is stored in the inductor. When the current increases, the derivative is positive and hence the power is positive; and, in turn, an additional energy is stored in the inductor. The energy stored in the inductor, W_L, is given by

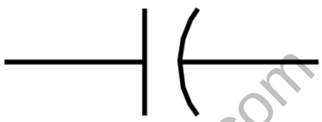
$$\boxed{W_L = \int_0^t vidt = \int_0^t Li\frac{di}{dt}dt = L\int_0^t idi = \frac{1}{2}Li^2}\ \text{Joule} \qquad \text{(Eq – 5)}$$

Eq – 5 assumes that the inductor has no previous history, that is, at $t = 0, i = 0.$ the energy is stored in the inductor in a magnetic field. When the current increases, the stored energy is the magnetic field also increases. When the current reduces to zero, the energy stored in the inductor is returned to the source from which it receives the energy.

Capacitors:

A *capacitor* is a device that can store energy in the form of a charge separation when it is suitably polarized by an electric field by applying a voltage across it. In the simplest form, a capacitor consists of two parallel conducting plates separated by air or any insulating material, such as mica. It has the characteristic of storing electric energy (charge), which can be fully retrieved, in an electric field. A significant feature of the capacitor is that its presence is felt in an electric circuit when a changing potential difference exists across the capacitor. The presence of an insulating material between the conducting plates does not allow the flow of dc current; thus a capacitor acts as an open circuit in the presence of dc current.

- Denoted as C
- Unit is Farad (F).
- Symbol



(Schematic representation of a capacitor.)

The ability of the capacitor is store charge is measured in terms of capacitance C. *Capacitance* of a capacitor is defined as charge stored per volt applied and its unit is farad (F). However, for practical purposes the unit of farad is too large. Hence, microfarad (μ F) is used to specify the capacitance of the components and circuits.

If the charge on the capacitor at any time t after the switch S is closed in q coulombs and the voltage across it is v volts. Then by definition

$$\boxed{C = \frac{q}{v}} \text{ coulomb} \qquad \text{(Eq – 6)}$$

Current i flowing through the capacitor can be obtained as

$$\boxed{i = \frac{dq}{dt} = C\,\frac{dv}{dt}} \text{ Ampere} \qquad \text{(Eq – 7)}$$

Eq – 7 is integrated with respect to time to get the voltage across the capacitor as

$$\boxed{v = \frac{1}{C}\int_0^t idt + v(0)} \qquad \text{(Eq – 8)}$$

Where $v(0)$ denotes the initial voltage across the capacitor at t = 0.

Power p in the capacitor is given as

$$\boxed{p = vi = Cv\frac{dv}{dt}} \text{ Watts} \qquad \text{(Eq – 9)}$$

Energy stored in capacitor, W_C, is given by

$$\boxed{W_C = \int p\,dt = C\int v\,dv = \frac{1}{2}Cv^2 \text{ joule}} \qquad \text{(Eq – 10)}$$

Capacitance of a capacitor depends on its dimensions :

A capacitor consists of two electrodes (plates) separated by a insulating material (dielectric). If the area of the plate in A m^2 and the distance between them is d m, it is observed that

$$\boxed{C \ \alpha\ A} \quad \text{and} \quad \boxed{C\ \alpha\ \frac{1}{d}}$$

$$\therefore \quad \boxed{C = \frac{\varepsilon A}{d}} \qquad \text{(Eq – 11)}$$

Where ε is the absolute permittivity constant. The absolute permittivity constant depends on the type of dielectric employed in the capacitor. The ratio of the absolute permittivity constant of the dielectric ε to the permittivity constant of vacuum ε_0 is called relative permittivity ε_r, that is,

$$\boxed{\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}}$$

Hence,

$$\boxed{\varepsilon = \varepsilon_0 \varepsilon_r}$$

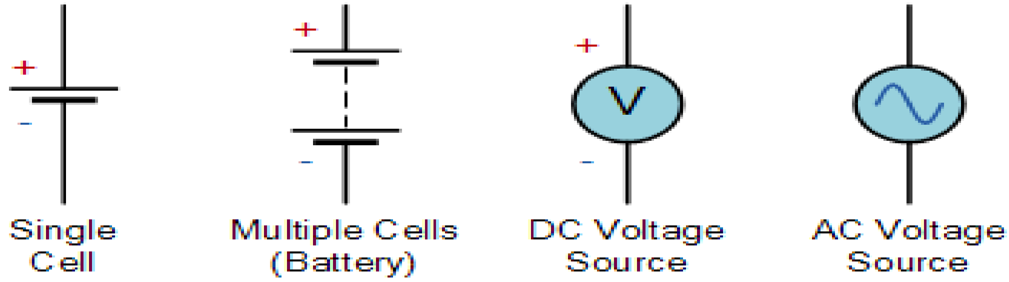
The units for absolute permittivity ε can be established from Eq.11 as under:

$$\boxed{\varepsilon = \frac{C(\text{farads}) \times d(\text{meters})}{A(\text{meters})^2} = \frac{C \times d}{A}} \ (\text{farads / metre}(F/m))$$

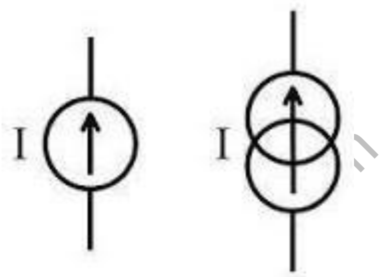
Based on experimental results, the value of the permittivity constant of vacuum has been found to be equal to 8.85×10^{-12} F/m. Therefore, the value of ε_r for vacuum is 1.0 and for air is 1.0006. For practical purposes, the value of ε_r for air is also taken as 1.

VOLTAGE SOURCE

It is a two terminal device which can maintain a fixed voltage. An ideal voltage source can maintain the fixed voltage independent of the load resistance or the output current. However, a real-world voltage source cannot supply unlimited current. A voltage source is the dual of a current source. Real-world sources of electrical energy, such as batteries, generators, and power systems, can be modeled for analysis purposes as a combination of an ideal voltage source.



CURRENT SOURCE -is an electronic circuit that delivers or absorbs an electric current which is independent of the voltage across it. A current source is the dual of a voltage source.The term constant-current 'sink' is sometimes used for sources fed from a negative voltage supply. Figure 1 shows the schematic symbol for an ideal current source, driving a resistor load There are two types - an independent current source (or sink) delivers a constant current. A dependent current source delivers a current which is proportional to some other voltage or current in the circuit.



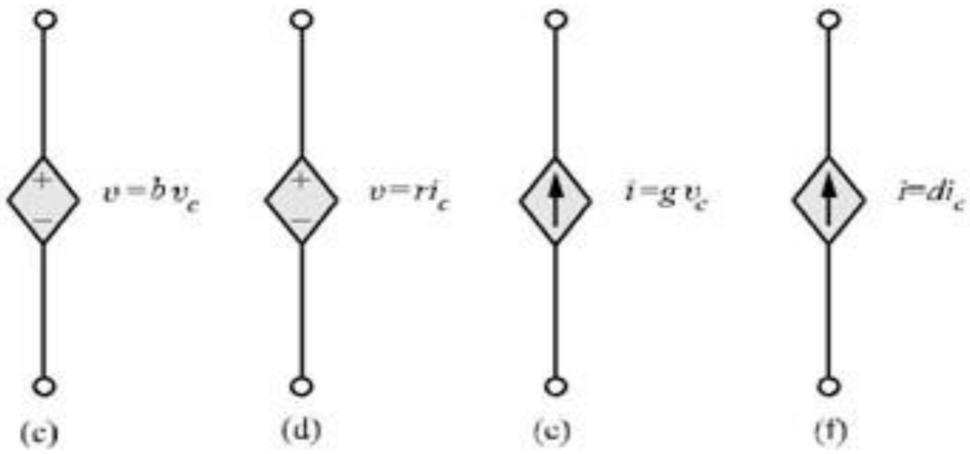
Independent Sources -The ideal voltage source and ideal current source discussed here come under the category of *independent sources*. The independent source is one which does not depend on any other quantity in the circuit. It has a constant value i.e., the strength of voltage or current is not changed by any variation in the connected circuit. Thus, the voltage or current is fixed and is not adjustable.

Dependent Sources: The source whose output voltage or current is not fixed but depends on the voltage or current in another part of the circuit is called as dependent or controlled source.

The dependent source is basically a three terminal device. The three terminals are paired with one common terminal. One pair is referred as input while the other pair as output. For example, in a transistor, the output voltage depends upon the input voltage. The dependent sources are represented by diamond shaped box as shown in Fig.

The dependent sources can be categorized as:

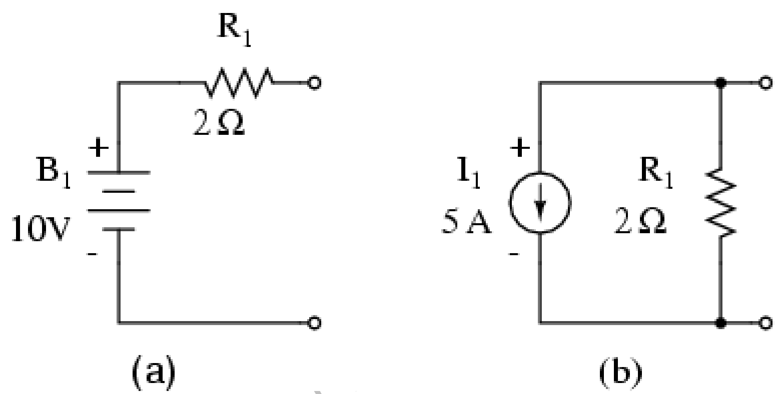
c. Voltage dependent voltage source
d. Current dependent voltage source
e. Voltage dependent current source
f. Current dependent current source



SOURCE CONVERSION

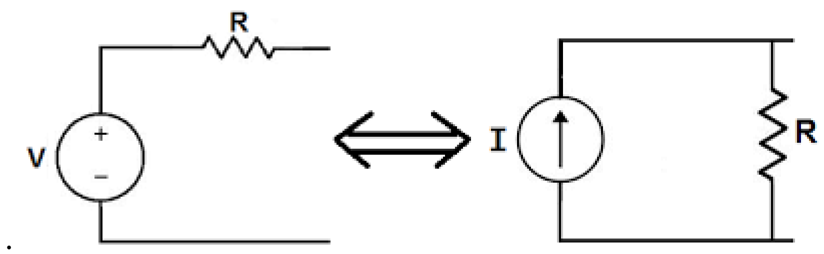
It is most important part of the circuit analysis. To simplify the circuit, certain rules have been framed which are given below:

(a) A voltage source having some resistance can be replaced by the current source in parallel with the resistance as shown in Fig.



$I_1 = B_1/R_1 = 10/2 = 5\text{ A}$

(b) A current source in parallel with some resistance can be replaced by a voltage source in series with the same resistance as shown in fig.



Ohms Law

The relationship between Voltage, Current and Resistance in any DC electrical circuit was firstly discovered by the German physicist **Georg Ohm**.**Ohm** found that, at a constant temperature, the electrical current flowing through a fixed linear resistance is directly proportional to the voltage applied across it, and also inversely proportional to the resistance.

Ohms Law Relationship

$$\text{Current}, (I) = \frac{\text{Voltage}, (V)}{\text{Resistance}, (R)} \text{ in Amperes}, (A)$$

By knowing any two values of the Voltage, Current or Resistance quantities we can use **Ohms Law** to find the third missing value. **Ohms Law** is used extensively in electronics formulas and calculations so it is "very important to understand and accurately remember these formulas"

To find the Voltage, (V)

[V = I x R](volts) = I (amps) x R (Ω)

To find the Current, (I)

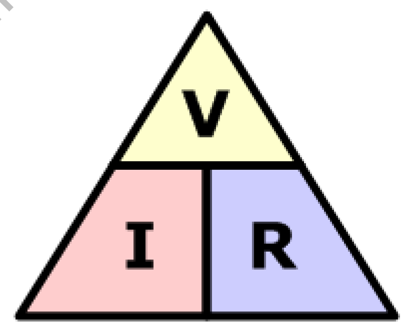
[$I = \frac{V}{R}$] I (amps) = V (volts) ÷ R (Ω)

To find the Resistance, (R)

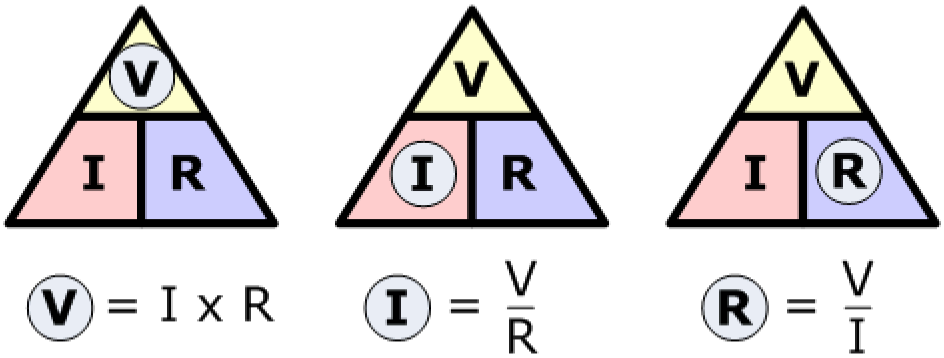
[$R = \frac{V}{I}$] R (Ω) = V (volts) ÷ I (amps)

It is sometimes easier to remember this Ohms law relationship by using pictures. Here the three quantities of V, I and R have been superimposed into a triangle (affectionately called the **Ohms Law Triangle**) giving voltage at the top with current and resistance below. This arrangement represents the actual position of each quantity within the Ohms law formulas.

Ohms Law Triangle

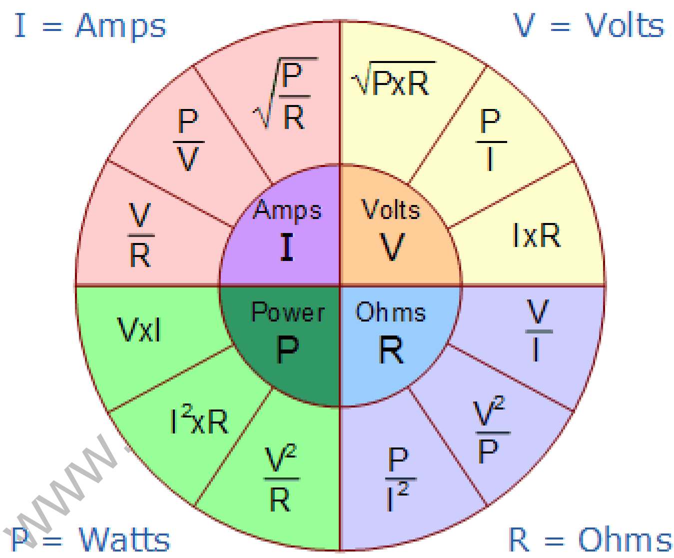


Transposing the standard Ohms Law equation above will give us the following combinations of the same equation:



Then by using Ohms Law we can see that a voltage of 1V applied to a resistor of 1Ω will cause a current of 1A to flow and the greater the resistance value, the less current that will flow for a given applied voltage. Any Electrical device or component that obeys "Ohms Law" that is, the current flowing through it is proportional to the voltage across it (I α V), such as resistors or cables, are said to be**"Ohmic"** in nature, and devices that do not, such as transistors or diodes, are said to be **"Non-ohmic"** devices.

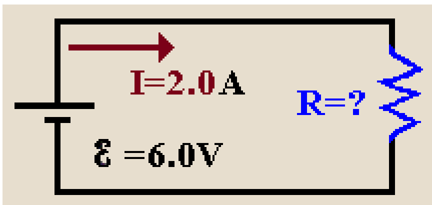
Ohms Law Pie Chart



Ohms Law Matrix Table

Ohms Law Formulas				
Known Values	Resistance (R)	Current (I)	Voltage (V)	Power (P)
Current & Resistance	---	---	$V = I \times R$	$P = I^2 \times R$
Voltage & Current	$R = \frac{V}{I}$	---	---	$P = V \times I$
Power & Current	$R = \frac{P}{I^2}$	---	$V = \frac{P}{I}$	---
Voltage & Resistance	---	$I = \frac{V}{R}$	---	$P = \frac{V^2}{R}$
Power & Resistance	---	$I = \sqrt{\frac{P}{R}}$	$V = \sqrt{P \times R}$	---
Voltage & Power	$R = \frac{V^2}{P}$	$I = \frac{P}{V}$	---	---

Question 1:
An emf source of 6.0V is connected to a purely resistive lamp and a current of 2.0 amperes flows. All the wires are resistance-free. What is the resistance of the lamp?



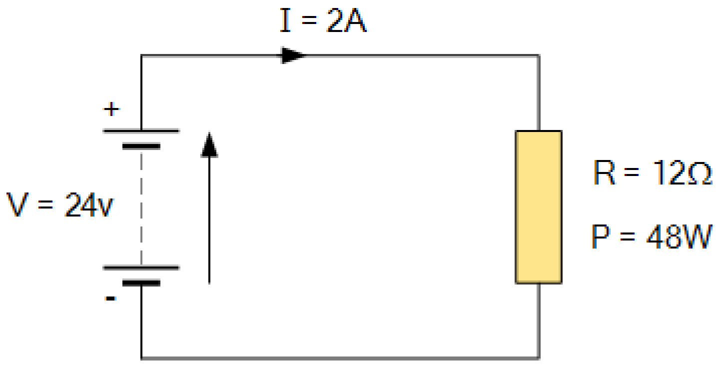
Solution: The gain of potential energy occurs as a charge passes through the battery, that is, it gains a potential of E =6.0V. No energy is lost to the wires, since they are assumed to be resistance-free. By conservation of energy, the potential that was gained (i.e. =V=6.0V) must be lost in the resistor. So, by Ohm's Law:

$$V = I\,R$$

$$R = \frac{V}{I}$$

$$R = 3.0\ \Omega$$

Problem 2: For the circuit shown below find the Voltage (V), the Current (I), the Resistance (R) and the Power (P).



Voltage [V = I x R] = 2 x 12Ω = 24V

Current [I = V ÷ R] = 24 ÷ 12Ω = 2A

Resistance [R = V ÷ I] = 24 ÷ 2 = 12 Ω

Power [P = V x I] = 24 x 2 = 48W

Power within an electrical circuit is only present when **BOTH** voltage and current are present. For example, in an open-circuit condition, voltage is present but there is no current flow I = 0 (zero), therefore V x 0 is 0 so the power dissipated within the circuit must also be 0. Likewise, if we have a short-circuit condition, current flow is present but there is no voltage V = 0, therefore 0 x I = 0 so again the power dissipated within the circuit is 0.

As electrical power is the product of V x I, the power dissipated in a circuit is the same whether the circuit contains high voltage and low current or low voltage and high current flow. Generally, electrical power is dissipated in the form of **Heat** (heaters), **Mechanical Work** such as motors, **Energy**in the form of radiated (Lamps) or as stored energy (Batteries).

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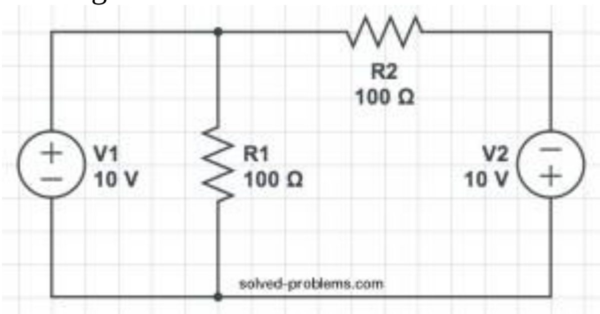
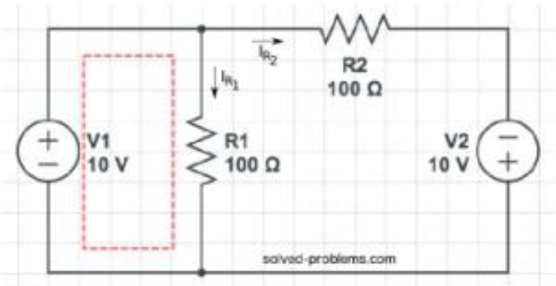
Problem:

Find resistor currents using



Solution:

R_1 and V_1 are parallel. So the voltage across R_1 is equal to V_1 . This can be also calculated using KVL in the left hand side loop:



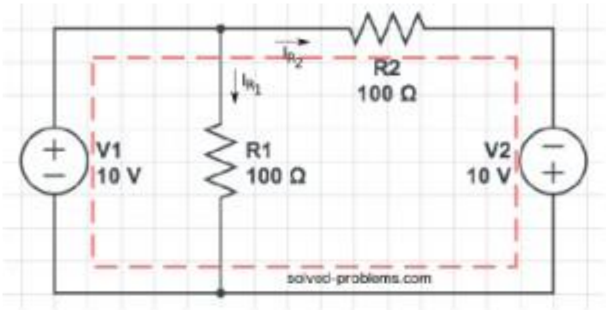
$-V_1 + V_{R_1} = 0 \rightarrow V_{R_1} = V_1 = 10V$.

Now, use Ohm's law to find I_{R_1} :

$V_{R_1} = R_1 \times I_{R_1} \rightarrow I_{R_1} = \frac{V_{R_1}}{R_1} = 0.1A$.

To find I_{R_2} , write KVL around the outer loop:

KVL.



$$-V_1 + V_{R_2} - V_2 = 0 \rightarrow V_{R_2} = V_1 + V_2 = 20V.$$

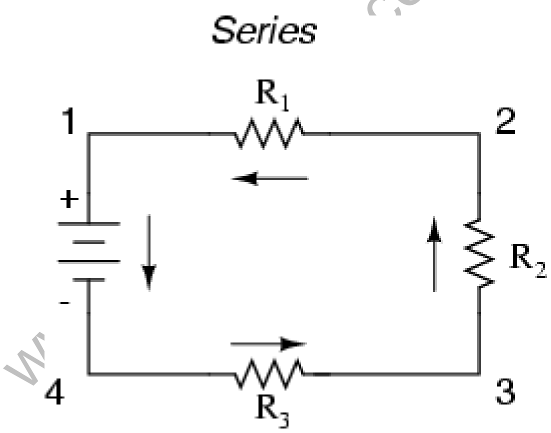
Again, use Ohm's law to determine I_{R_2}:

$$V_{R_2} = R_2 \times I_{R_2} \rightarrow I_{R_2} = \frac{V_{R_2}}{R_2} = 0.2A.$$

Series and Parallel Circuits

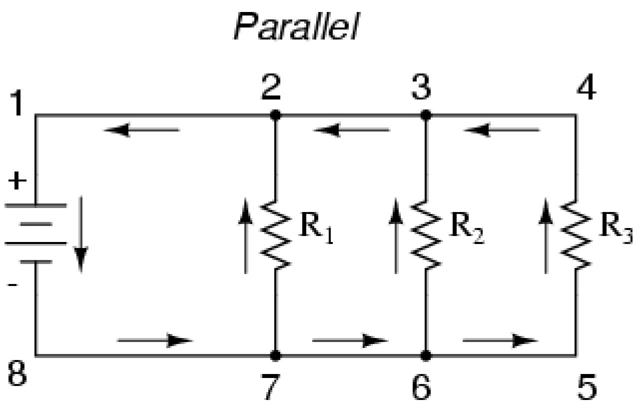
Circuits consisting of just one battery and one load resistance are very simple to analyze, but they are not often found in practical applications. Usually, we find circuits where more than two components are connected together.

There are two basic ways in which to connect more than two circuit components: *series* and *parallel*. First, an example of a series circuit:



Here, we have three resistors (labeled R_1, R_2, and R_3), connected in a long chain from one terminal of the battery to the other. (It should be noted that the subscript labeling—those little numbers to the lower-right of the letter "R"—are unrelated to the resistor values in ohms. They serve only to identify one resistor from another.) The defining characteristic of a series circuit is that there is only one path for electrons to flow. In this circuit the electrons flow in a counter-clockwise direction, from point 4 to point 3 to point 2 to point 1 and back around to 4.

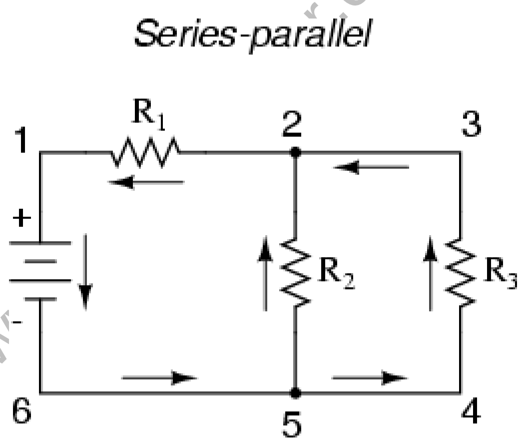
Now, let's look at the other type of circuit, a parallel configuration:



Again, we have three resistors, but this time they form more than one continuous path for electrons to flow. There's one path from 8 to 7 to 2 to 1 and back to 8 again. There's another from 8 to 7 to 6 to 3 to 2 to 1 and back to 8 again. And then there's a third path from 8 to 7 to 6 to 5 to 4 to 3 to 2 to 1 and back to 8 again. Each individual path (through R_1, R_2, and R_3) is called a *branch*.

The defining characteristic of a parallel circuit is that all components are connected between the same set of electrically common points. Looking at the schematic diagram, we see that points 1, 2, 3, and 4 are all electrically common. So are points 8, 7, 6, and 5. Note that all resistors as well as the battery are connected between these two sets of points.

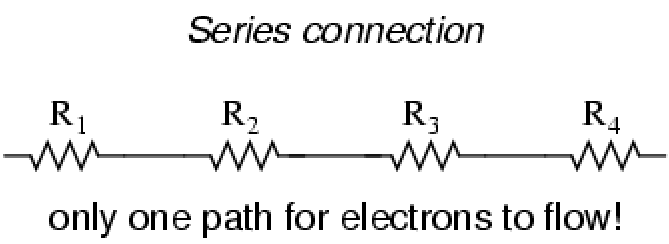
And, of course, the complexity doesn't stop at simple series and parallel either! We can have circuits that are a combination of series and parallel, too:



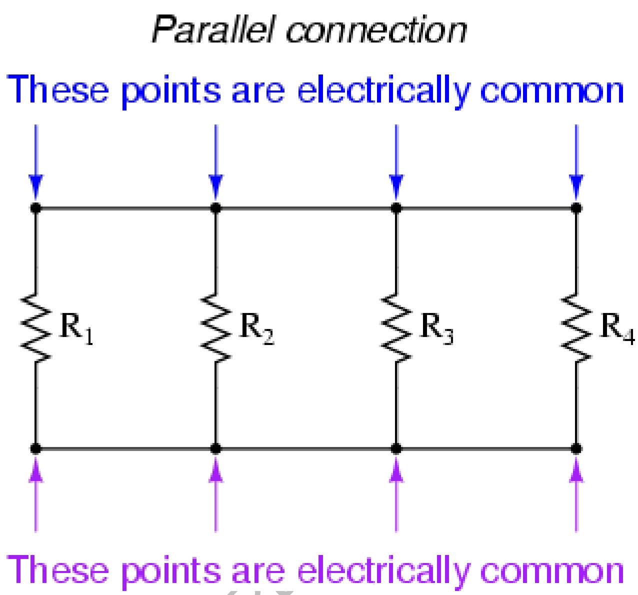
In this circuit, we have two loops for electrons to flow through: one from 6 to 5 to 2 to 1 and back to 6 again, and another from 6 to 5 to 4 to 3 to 2 to 1 and back to 6 again. Notice how both current paths go through R_1 (from point 2 to point 1). In this configuration, we'd say that R_2 and R_3 are in parallel with each other, while R_1 is in series with the parallel combination of R_2 and R_3.

This is just a preview of things to come. Don't worry! We'll explore all these circuit configurations in detail, one at a time!

The basic idea of a "series" connection is that components are connected end-to-end in a line to form a single path for electrons to flow:



The basic idea of a "parallel" connection, on the other hand, is that all components are connected across each other's leads. In a purely parallel circuit, there are never more than two sets of electrically common points, no matter how many components are connected. There are many paths for electrons to flow, but only one voltage across all components:

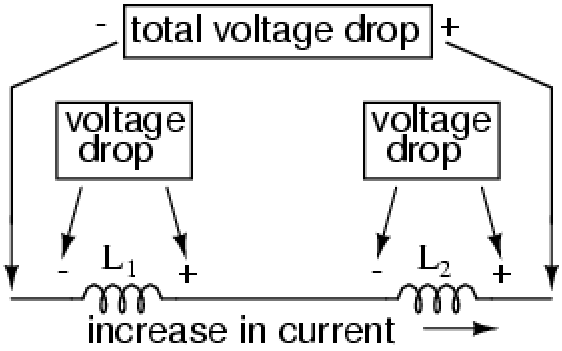


Series and parallel resistor configurations have very different electrical properties. We'll explore the properties of each configuration in the sections to come.

- **REVIEW:**
- In a series circuit, all components are connected end-to-end, forming a single path for electrons to flow.
- In a parallel circuit, all components are connected across each other, forming exactly two sets of electrically common points.
- A "branch" in a parallel circuit is a path for electric current formed by one of the load components (such as a resistor).

Inductors in Series and Parallel:

When inductors are connected in series, the total inductance is the sum of the individual inductors' inductances. To understand why this is so, consider the following: the definitive measure of inductance is the amount of voltage dropped across an inductor for a given rate of current change through it. If inductors are connected together in series (thus sharing the same current, and seeing the same rate of change in current), then the total voltage dropped as the result of a change in current will be additive with each inductor, creating a greater total voltage than either of the individual inductors alone. Greater voltage for the same rate of change in current means greater inductance.

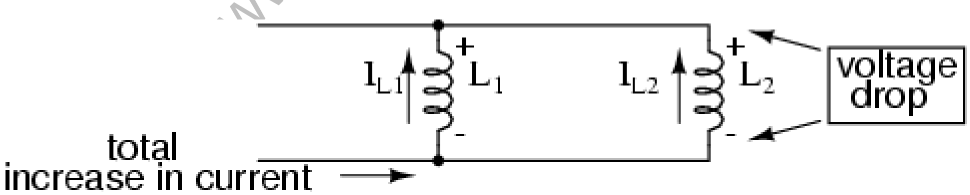


Thus, the total inductance for series inductors is more than any one of the individual inductors' inductances. The formula for calculating the series total inductance is the same form as for calculating series resistances:

Series Inductances

$$L_{total} = L_1 + L_2 + \ldots L_n$$

When inductors are connected in parallel, the total inductance is less than any one of the parallel inductors' inductances. Again, remember that the definitive measure of inductance is the amount of voltage dropped across an inductor for a given rate of current change through it. Since the current through each parallel inductor will be a fraction of the total current, and the voltage across each parallel inductor will be equal, a change in total current will result in less voltage dropped across the parallel array than for any one of the inductors considered separately. In other words, there will be less voltage dropped across parallel inductors for a given rate of change in current than for any of those inductors considered separately, because total current divides among parallel branches. Less voltage for the same rate of change in current means less inductance.



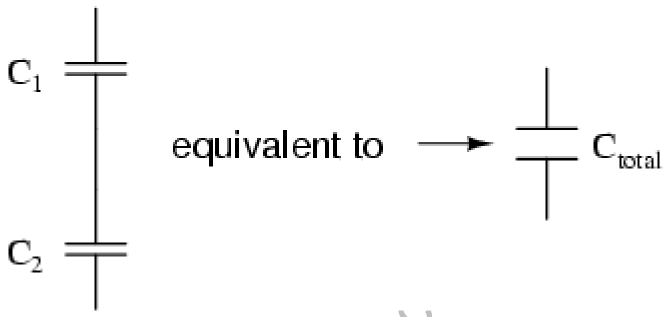
Thus, the total inductance is less than any one of the individual inductors' inductances. The formula for calculating the parallel total inductance is the same form as for calculating parallel resistances:

Parallel Inductances

$$L_{total} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \ldots \frac{1}{L_n}}$$

Capacitors in series and parallel:

When capacitors are connected in series, the total capacitance is less than any one of the series capacitors' individual capacitances. If two or more capacitors are connected in series, the overall effect is that of a single (equivalent) capacitor having the sum total of the plate spacings of the individual capacitors. As we've just seen, an increase in plate spacing, with all other factors unchanged, results in decreased capacitance.

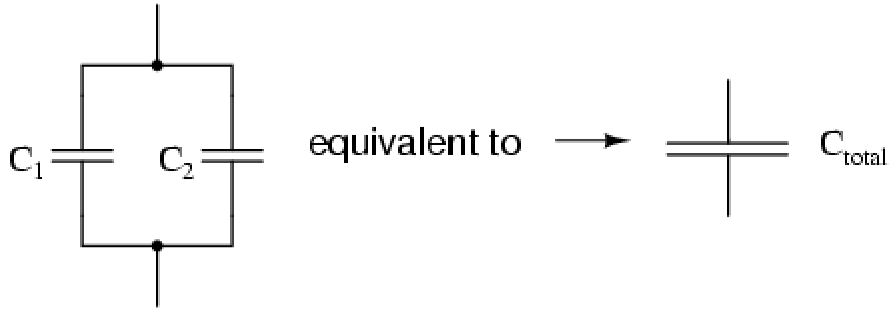


Thus, the total capacitance is less than any one of the individual capacitors' capacitances. The formula for calculating the series total capacitance is the same form as for calculating parallel resistances:

Series Capacitances

$$C_{total} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \ldots \frac{1}{C_n}}$$

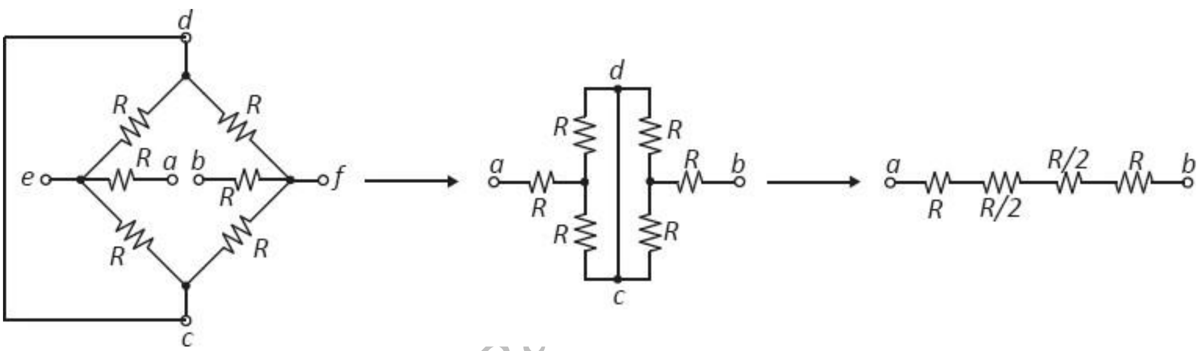
When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors' capacitances. If two or more capacitors are connected in parallel, the overall effect is that of a single equivalent capacitor having the sum total of the plate areas of the individual capacitors. As we've just seen, an increase in plate area, with all other factors unchanged, results in increased capacitance.

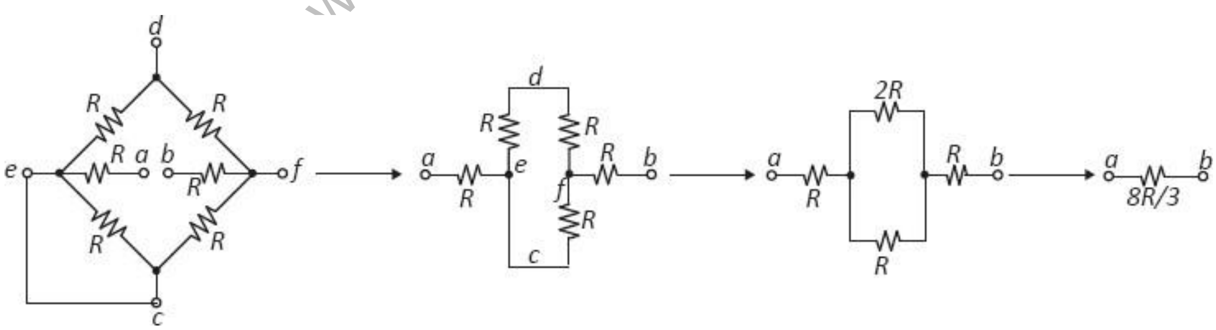


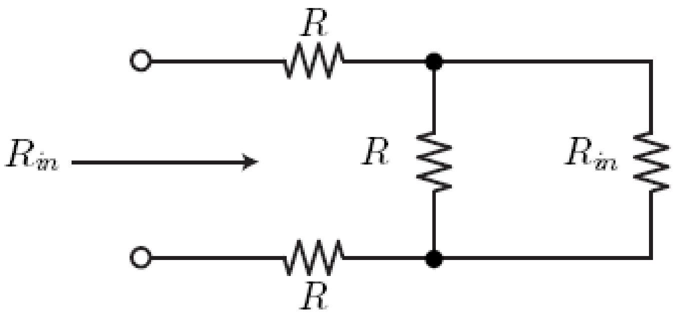
Thus, the total capacitance is more than any one of the individual capacitors' capacitances. The formula for calculating the parallel total capacitance is the same form as for calculating series resistances:

Parallel Capacitances

$$C_{total} = C_1 + C_2 + \ldots\ C_n$$







Introduction to PORT NETWORKS

There are certain circuit configurations that cannot be simplified by series-parallel combination alone. A simple transformation based on mathematical technique is readily simplifies the electrical circuit configuration. A circuit configuration shown below

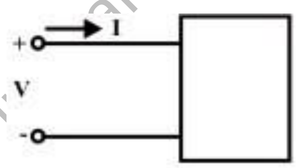


Fig. 6.1(a) One port network

is a general **one-port circuit.** When any voltage source is connected across the terminals, the current entering through any one of the two terminals, equals the current leaving the other terminal. For example, resistance, inductance and capacitance acts as a **one-port.** On the other hand, a **two-port** is a circuit having two pairs of terminals. Each pair behaves as a one-port; current entering in one terminal must be equal to the current living the other terminal.

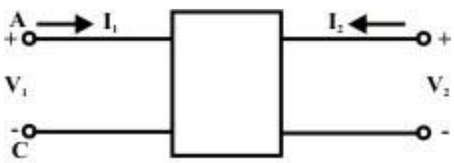


Fig. 6.1(b) Two port network

Fig.6.1.(b) can be described as a four terminal network, for convenience subscript 1 to refer to the variables at the input port (at the left) and the subscript 2 to refer to the variables at the output

port (at the right). The most important subclass of two-port networks is the one in which the minus reference terminals of the input and output ports are at the same. This circuit configuration is readily possible to consider the ‘π’ or ‘Δ’ – network also as a three-terminal network in fig.6.1(c). Another frequently encountered circuit configuration that shown in fig.6.1(d) is approximately referred to as a three-terminal *Y* connected circuit as well as two-port circuit.

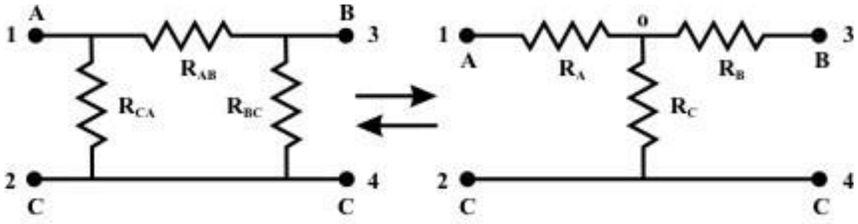


Fig. 6.1 (c) Fig. 6.1 (d)

The name derives from the shape or configuration of the circuit diagrams, which look respectively like the letter Y and the Greek capital letter Δ.

Delta – Wye conversion (Δ) (Y)

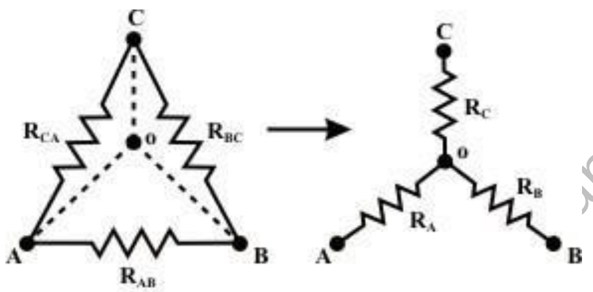


Fig. 6.1 (e)

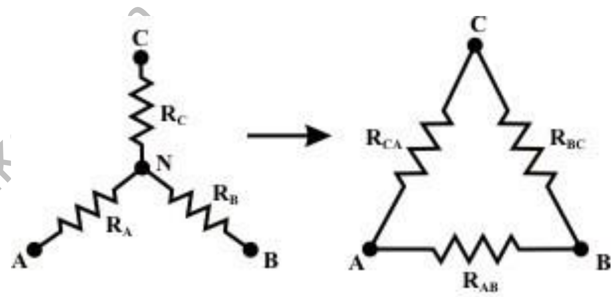


Fig. 6.1 (f)

These configurations may often be handled by the use of a $\Delta{-}Y$ or $-\Delta Y$ transformation. One of the most basic three-terminal network equivalent is that of three resistors connected in “Delta” Δ and in “Wye(Y)”. These two circuits identified in fig.L6.1 (e) and Fig.L.6.1 (f) are sometimes part of a larger circuit and obtained their names from their configurations. These three terminal networks can be redrawn as four-terminal networks as shown in fig.L.6.1(c) and fig.L.6.1 (d). We can obtain useful expression for direct transformation or conversion from Δ to *Y* or *Y* to Δ by considering that for equivalence the two networks have the same resistance when looked at the similar pairs of terminals.

Conversion from Delta (Δ) to Star or Wye (Y)

Let us consider the network shown in fig.6.1(e) and assumed the resistances (*RAB,RBC and RCA*) in Δ network are known. Our problem is to find the values of in Wye (*Y*) network (see fig.6.1(e)) that will produce the same resistance when measured between similar pairs of terminals. We can write the equivalence resistance between any two terminals in the following form.

Between A & C terminals:

$$R_A + R_C = \frac{R_{CA}\left(R_{AB}+R_{BC}\right)}{R_{AB}+R_{BC}+R_{CA}}$$

Between C & B terminals:

$$R_C + R_B = \frac{R_{BA}\left(R_{AB}+R_{CA}\right)}{R_{AB}+R_{BC}+R_{CA}}$$

Between B & A terminals:

$$R_B + R_A = \frac{R_{AB}\left(R_{CA}+R_{BC}\right)}{R_{AB}+R_{BC}+R_{CA}}$$

By combining above three equations, one can write an expression as given below.

$$R_A + R_B + R_C = \frac{R_{AB}R_{BC}+R_{BC}R_{CA}+R_{CA}R_{AB}}{R_{AB}+R_{BC}+R_{CA}}$$

we can write the express for unknown resistances of Wye (Y) network as

$$R_A = \frac{R_{AB}R_{CA}}{R_{AB}+R_{BC}+R_{CA}}$$

$$R_B = \frac{R_{AB}R_{BC}}{R_{AB}+R_{BC}+R_{CA}}$$

$$R_C = \frac{R_{BC}R_{CA}}{R_{AB}+R_{BC}+R_{CA}}$$

When we need to transform a Delta (Δ) network to an equivalent Wye (Y) network, the equations (6.5) to (6.7) are the useful expressions. On the other hand, the equations (6.12) – (6.14) are used for Wye (Y) to Delta (Δ) conversion.

Conversion from Star(Y) or Wye to Delta (Δ)

To convert a **Wye (Y)** to a **Delta (Δ)**, the relationships R_{AB}, R_{BC} *and* R_{CA} must be obtained in terms of the **Wye** resistances R_A R_B *and* R_C (referring to fig.6.1 (f)). Considering the Y connected network, we can write the current expression through RA resistor as

$$I_A = \frac{\left(V_A - V_N\right)}{R_A} \quad (\text{for} \quad Y \, \text{network})$$

Appling KCL at '' for Y connected network (assume N,,ABC terminals having higher potential than the terminal) we have,

$$\frac{(V_A - V_N)}{R_A} + \frac{(V_B - V_N)}{R_B} + \frac{(V_C - V_N)}{R_C} = 0 \quad \Rightarrow V_N\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right) = \left(\frac{V_A}{R_A} + \frac{V_B}{R_B} + \frac{V_C}{R_C}\right)$$

or, $$\Rightarrow V_N = \frac{\left(\frac{V_A}{R_A} + \frac{V_B}{R_B} + \frac{V_C}{R_C}\right)}{\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right)}$$

For Δ-network (see fig.6.1.(f)),
Current entering at terminal A = Current leaving the terminal 'A'

$$I_A = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}} \text{ (for } \Delta \text{ network)} \tag{6.10}$$

From equations (6.8) and (6.10),

$$\frac{(V_A - V_N)}{R_A} = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}}$$

Using the V_N expression in the above equation, we get

$$\frac{\left(V_A - \frac{\left(\frac{V_A}{R_A} + \frac{V_B}{R_B} + \frac{V_C}{R_C}\right)}{\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right)}\right)}{R_A} = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}} \quad \Rightarrow \frac{\left(\frac{\left(\frac{V_A - V_B}{R_B} + \frac{V_A - V_C}{R_C}\right)}{\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right)}\right)}{R_A} = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}}$$

or $$\frac{\left(\frac{\left(\frac{V_{AB}}{R_B} + \frac{V_{AC}}{R_C}\right)}{\left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C}\right)}\right)}{R_A} = \frac{V_{AB}}{R_{AB}} + \frac{V_{AC}}{R_{AC}} \tag{6.11}$$

Equating the coefficients of V_{AB} and V_{AC} in both sides of eq.(6.11), we obtained the following relationship.

$$\frac{1}{R_{AB}} = \frac{1}{R_A R_B\left(\frac{1}{R_A}+\frac{1}{R_B}+\frac{1}{R_C}\right)} \Rightarrow R_{AB} = R_A + R_B + \frac{R_A R_B}{R_C}$$

$$\frac{1}{R_{AC}} = \frac{1}{R_A R_C\left(\frac{1}{R_A}+\frac{1}{R_B}+\frac{1}{R_C}\right)} \Rightarrow R_{AC} = R_A + R_C + \frac{R_A R_C}{R_B}$$

Similarly, I_B for both the networks (see fig.61(f)) are given by

$$I_B = \frac{(V_B - V_N)}{R_B} \quad \text{(for } Y \text{ network)}$$

$$I_B = \frac{V_{BC}}{R_{BC}} + \frac{V_{BA}}{R_{BA}} \quad \text{(for } \Delta \text{ network)}$$

Equating the above two equations and using the value of V_N (see eq.(6.9), we get the final expression as

$$\frac{\left(\frac{\left(\frac{V_{BC}}{R_C}+\frac{V_{BA}}{R_A}\right)}{\left(\frac{1}{R_A}+\frac{1}{R_B}+\frac{1}{R_C}\right)}\right)}{R_B} = \frac{V_{BC}}{R_{BC}} + \frac{V_{BA}}{R_{BA}}$$

Equating the coefficient of V_{BC} in both sides of the above equations we obtain the following relation

$$\frac{1}{R_{BC}} = \frac{1}{R_B R_C\left(\frac{1}{R_A}+\frac{1}{R_B}+\frac{1}{R_C}\right)} \Rightarrow R_{BC} = R_B + R_C + \frac{R_B R_C}{R_A} \qquad (6.14)$$

When we need to transform a Delta (Δ) network to an equivalent Wye (Y) network, the equations (6.5) to (6.7) are the useful expressions. On the other hand, the equations (6.12) – (6.14) are used for Wye (Y) to Delta (Δ) conversion.

2. D.C. GENERATORS

Introduction

Although a far greater percentage of the electrical machines in service are a.c. machines, the d.c. machines are of considerable industrial importance. The principal advantage of the d.c. machine, particularly the d.c. motor, is that it provides a fine control of speed. Such an advantage is not claimed by any a.c. motor. However, d.c. generators are not as common as they used to be, because direct current, when required, is mainly obtained from an a.c. supply by the use of rectifiers. Nevertheless, an understanding of d.c. generator is important because it represents a logical introduction to the behavior of d.c. motors. Indeed many d.c. motors in industry actually operate as d.c. generators for a brief period.

Generator Principle

An electric generator is a machine that converts mechanical energy into electrical energy. An electric generator is based on the principle that whenever flux is cut by a conductor, an e.m.f. is induced which will cause a current to flow if the conductor circuit is closed. The direction of induced e.m.f. (and hence current) is given by Fleming's right hand rule. Therefore, the essential components of a generator are:

(a) a magnetic field
(b) conductor or a group of conductors
(c) motion of conductor w.r.t. magnetic field.

Simple Loop Generator

Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown in Fig.(1.1). As the loop rotates, the flux linking the coil sides AB and CD changes continuously. Hence the e.m.f. induced in these coil sides also changes but the e.m.f. induced in one coil side adds to that induced in the other.

(i) When the loop is in position no. 1 [See Fig. 1.1], the generated e.m.f. is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it

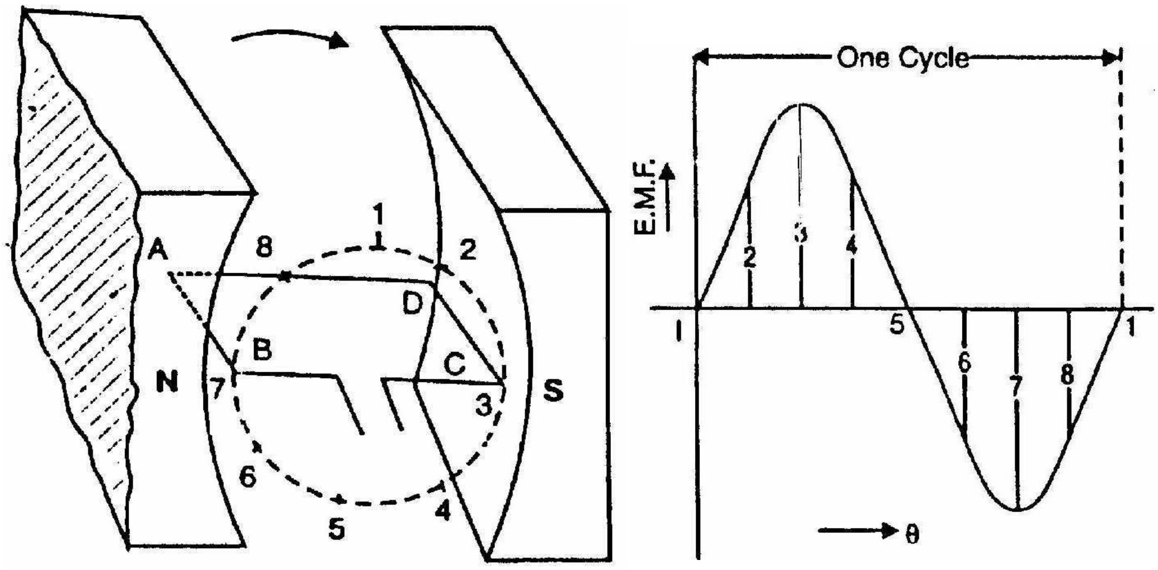
(ii) When the loop is in position no. 2, the coil sides are moving at an angle to the flux and, therefore, a low e.m.f. is generated as indicated by point 2 in Fig. (1.2).

(iii) When the loop is in position no. 3, the coil sides (AB and CD) are at right angle to the flux and are, therefore, cutting the flux at a maximum rate. Hence at this instant, the generated e.m.f. is maximum as indicated by point 3 in Fig. (1.2).

(iv) At position 4, the generated e.m.f. is less because the coil sides are cutting the flux at an angle.

(v) At position 5, no magnetic lines are cut and hence induced e.m.f. is zero as indicated by point 5 in Fig. (1.2).

(vi) At position 6, the coil sides move under a pole of opposite polarity and hence the direction of generated e.m.f. is reversed. The maximum e.m.f. in this direction (i.e., reverse direction, See Fig. 1.2) will be when the loop is at position 7 and zero when at position 1. This cycle repeats with each revolution of the coil.



Note that e.m.f. generated in the loop is alternating one. It is because any coilside, say AB has e.m.f. in one direction when under the influence of N-pole and in the other direction when under the influence of S-pole. If a load is connected across the ends of the loop, then alternating current will flow through the load.The alternating voltage generated in the loop can be converted into direct voltage by a device called commutator. We then have the d.c. generator. In fact, a commutator is a mechanical rectifier.

E.M.F. Equation of a D.C. Generator

Let ϕ = flux/pole in Wb
Z = total number of armature conductors
P = number of poles
A = number of parallel paths = 2 ... for wave winding
= P ... for lap winding
N = speed of armature in r.p.m.
E_g = e.m.f. of the generator = e.m.f./parallel path

Flux cut by one conductor in one revolution of the armature,

$d\phi = P\phi$ webers

Time taken to complete one revolution,

$dt = 60/N$ second

e.m.f generated/conductor $= \dfrac{d\phi}{dt} = \dfrac{P\phi}{60/N} = \dfrac{P\phi N}{60}$ volts

e.m.f. of generator,

E_g = e.m.f. per parallel path
= (e.m.f/conductor) × No. of conductors in series per parallel path

$$= \frac{P\phi\, N}{60} \times \frac{Z}{A}$$

$$\therefore \quad E_g = \frac{P\phi\, ZN}{60\, A}$$

where A = 2 for-wave winding

A= P for lap winding

Types of D.C. Generators

The magnetic field in a d.c. generator is normally produced by electromagnets rather than permanent magnets. Generators are generally classified according to their methods of field excitation. On this basis, d.c. generators are divided into the following two classes:

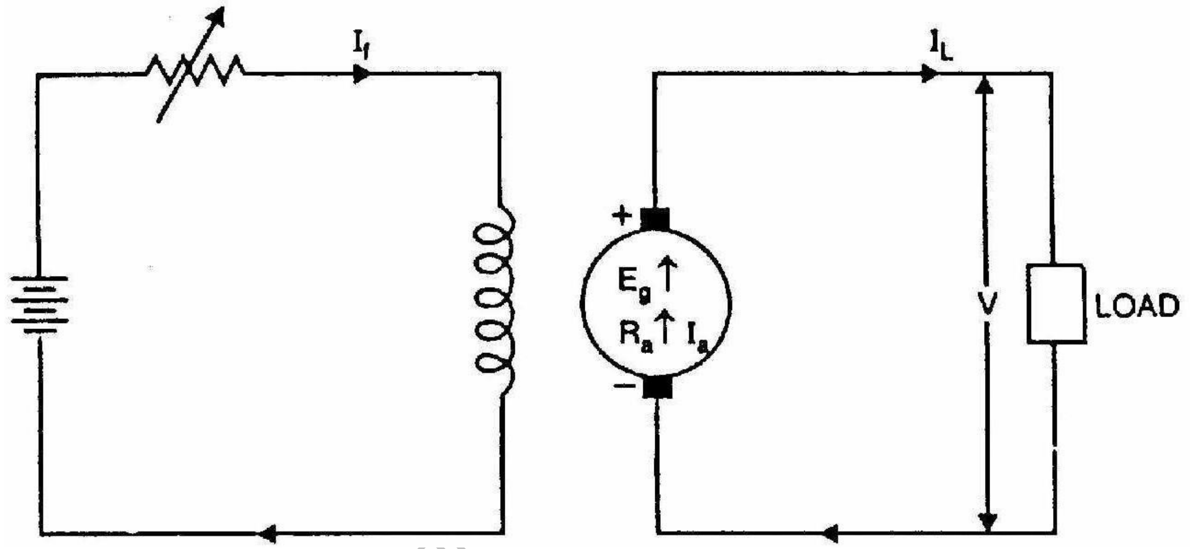
(i) Separately excited d.c. generators

(ii) Self-excited d.c. generators

The behaviour of a d.c. generator on load depends upon the method of field excitation adopted

Separately Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited generator. Fig. (1.32) shows the connections of a separately excited generator. The voltage output depends upon the speed of rotation of armature and the field current ($E_g = P\Phi ZN/60\ A$). The greater the speed and field current, greater is the generatede.m.f. It may be noted that separately excited d.c. generators are rarely used in practice. The d.c. generators are normally of self-excited type.



$$\text{Armature current, } I_a = I_L$$

$$\text{Terminal voltage, } V = E_g - I_aR_a$$

$$\text{Electric power developed} = E_gI_a$$

$$\text{Power delivered to load} = E_gI_a - I_a^2R_a = I_a\left(E_g - I_aR_a\right) = VI_a$$

Self-Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator. There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;

(i) Series generator;

(ii) Shunt generator;

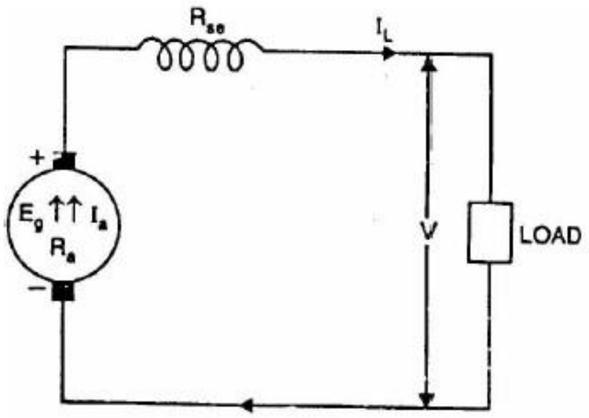
(iii) Compound generator

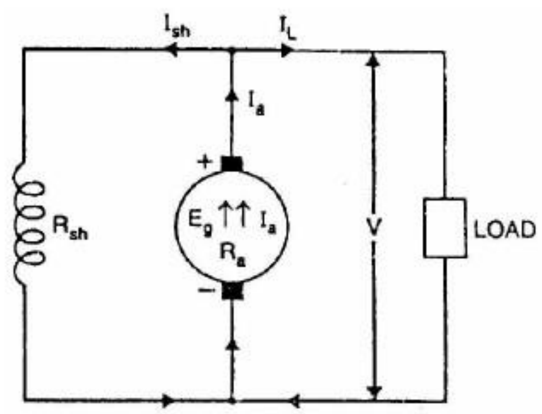
(i) Series generator

In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load. Fig. (1.33) shows the connections of a series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes e.g., as boosters.

Armature current, $I_a = I_{se} = I_L = I(say)$
Terminal voltage, $V = E_G - I(R_a + R_{se})$
Power developed in armature $= E_g I_a$
Power delivered to load

$$= E_g I_a - I_a^2(R_a + R_{se}) = I_a\left[E_g - I_a(R_a - R_{se})\right] = VI_a \text{ or } VI_L$$





(ii) Shunt generator

In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load. Fig. (1.34) shows the connections of a shunt-wound generator.

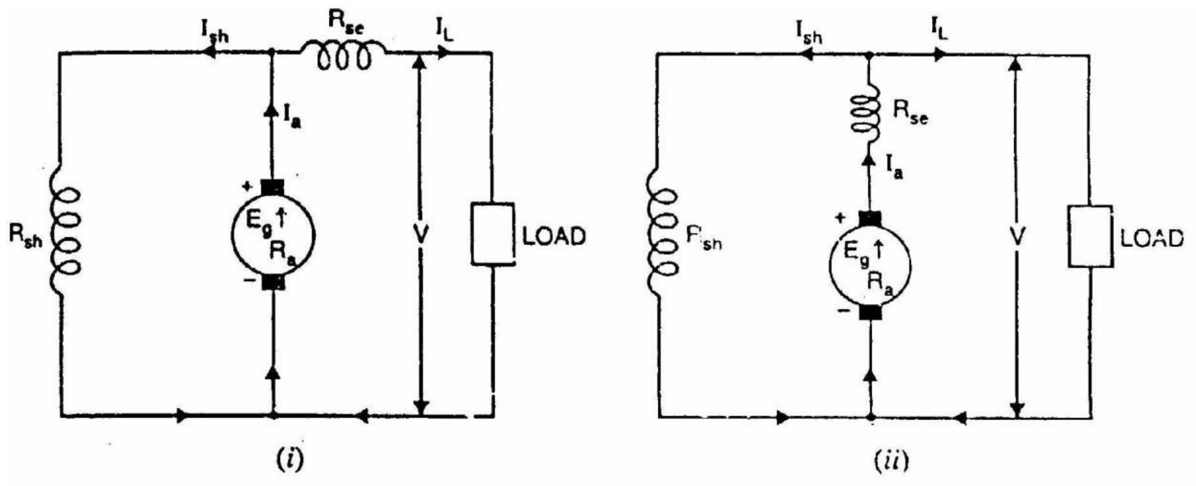
Shunt field current, $I_{sh} = V/R_{sh}$
Armature current, $I_a = I_L + I_{sh}$
Terminal voltage, $V = E_g - I_a R_a$
Power developed in armature $= E_g I_a$
Power delivered to load $= VI_L$

(iii) Compound generator

In a compound-wound generator, there are two sets of field windings on each pole one is in series and the other in parallel with the armature. A compound wound generator may be:

(a) Short Shunt in which only shunt field winding is in parallel with the armature winding [See Fig. (i)].

(b) Long Shunt in which shunt field winding is in parallel with both series field and armature winding [See Fig. (ii)].



Short shunt

Series field current, $I_{se} = I_L$

Shunt field current, $I_{sh} = \dfrac{V + I_{se}R_{se}}{R_{sh}}$

Terminal voltage, $V = E_g - I_aR_a - I_{se}R_{se}$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

Long shunt

Series field current, $I_{se} = I_a = I_L + I_{sh}$

Shunt field current, $I_{sh} = V/R_{sh}$

Terminal voltage, $V = E_g - I_a(R_a + R_{se})$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

Q A 4-pole d.c. shunt generator has an armature resistance of 0.018 Ω. The armature is lap-wound with 520 conductors. When driven at 750 rev/min the machine produces a total armature current of 400 A at a terminal voltage of 200 V. Calculate the useful flux/pole.

A

$$p = 2;\ a = 4;\ R_a = 0.018\,\Omega;\ z = 520;\ n = \frac{750}{60} = 12.5 \text{ rev/s}$$

$$I_a = 400 \text{ A};\ V = 200 \text{ V}$$

$$E = V + I_aR_a \text{ volt} = 200 + (400 \times 0.018)$$

$$E = 207.2 \text{ V}$$

$$E = \frac{2p\Phi zn}{a} \text{ volt}$$

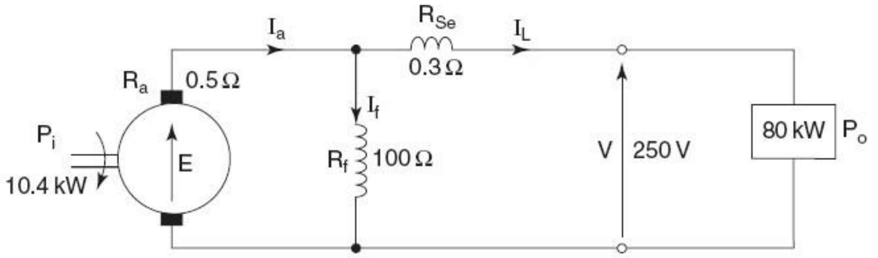
$$\text{so, } \Phi = \frac{Ea}{2pzn} \text{ weber} = \frac{207.2 \times 4}{4 \times 520 \times 12.5}$$

$$\Phi = 31.9 \text{ mWb } \textbf{Ans}$$

Q **A short-shunt compound generator has armature, shunt field and series field resistances of 0.5 Ω 100 Ω, and 0.3 Ω respectively. When supplying a load of 8 kW at a terminal voltage of 250 V the input power supplied by the driving motor is 10.4 kW. Calculate (a) the generated emf, (b) the efficiency, (c) the iron, friction and windage loss, and (d) the total fixed losses.**

A

$$R_a = 0.5\,\Omega;\ R_f = 100\,\Omega;\ R_{Se} = 0.3\,\Omega;\ P_o = 8000\text{W};\ V = 250\text{V};\ P_i = 10\,400\text{W}$$



(a) $$I_L = \frac{P_O}{V_L} \text{ amp} = \frac{8000}{250} = 32 \text{ A}$$

$$V_f = V + I_LR_{Se} \text{ volt} = 250 + (32 \times 0.3)$$

$$V_f = 259.6 \text{ V}$$

$$I_f = \frac{V_f}{R_f} \text{ amp} = \frac{259.6}{100} = 2.6 \text{ A}$$

$$I_a = I_L + I_f \text{ amp} = 32 + 2.6 = 34.6 \text{ A}$$

$$E = V_f + I_aR_a \text{ volt} = 259.6 + (34.6 \times 0.5)$$

$$E = 276.9 \text{ V } \textbf{Ans}$$

(b) $$\eta = \frac{P_o}{P_i} \times 100\% = \frac{8}{10.4} \times 100\%$$

$\eta = 76.92\%$ **Ans**

(c) From the power flow diagram

$$P_{Fe} = P_i - EI_a \text{ watt} = 10\,400 - (276.9 \times 34.6)$$

$P_{Fe} = 819.26$ W **Ans**

(d) $$\text{total fixed losses} = P_{Fe} + I_f^2 R_f \text{ watt}$$

$$= 819.26 + (2.6 \times 100)$$

total fixed losses $= 1.08$ kW **Ans**

D.C. Motors

Introduction

D. C. motors are seldom used in ordinary applications because all electric supply companies furnish alternating current However, for special applications such as in steel mills, mines and electric trains, it is advantageous to convert alternating current into direct current in order to use d.c. motors. The reason is that speed/torque characteristics of d.c. motors are much more superior to that of a.c. motors. Therefore, it is not surprising to note that for industrial drives, d.c. motors are as popular as 3-phase induction motors. Like d.c. generators, d.c. motors are also of three types viz., series-wound, shunt-wound and compound wound. The use of a particular motor depends upon the mechanical load it has to drive.

D.C. Motor Principle

A machine that converts d.c. power into mechanical power is known as a d.c. motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of this force is given by Fleming's left hand rule and magnitude is given by; FBInewtons

Basically, there is no constructional difference between a d.c. motor and a d.c. generator. The same d.c. machine can be run as a generator or motor

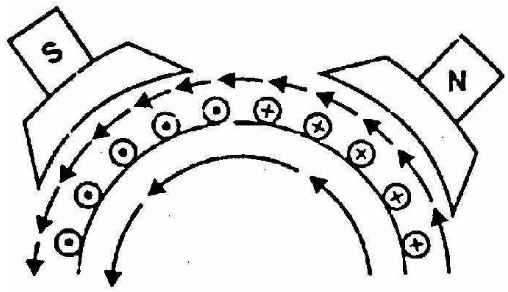
Working of D.C. Motor

Consider a part of a multipolar d.c. motor as shown in Fig. (4.1). When the terminals of the motor are connected to an external source of d.c. supply:

(i) the field magnets are excited developing alternate N and S poles

(ii) the armature conductors carry ^currents. All conductors under N-pole carry currents in one direction while all the conductors under S-pole carry currents in the opposite direction.

Suppose the conductors under N-pole carry currents into the plane of the paper and those under S-pole carry currents out of the plane of the paper as shown in Fig.(4.1). Since each armature conductor is carrying current and is placed in the magnetic field, mechanical force acts on it.



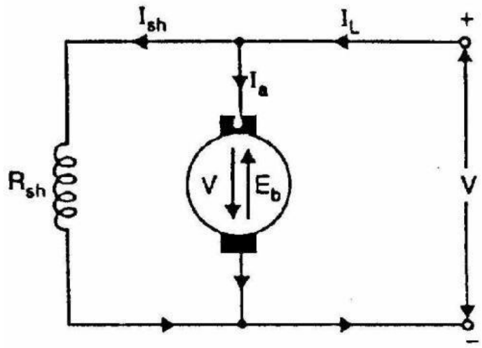
Referring to Fig. (4.1) and applying Fleming's left hand rule, it is clear that force on each conductor is tending to rotate the armature in anticlockwise direction. All these forces add together to produce a driving torque which sets the armature rotating.

When the conductor moves from one side of a brush to the other, the current in that conductor is reversed and at the same time it comes under the influence of next pole which is of opposite polarity.

Consequently, the direction of force on the conductor remains the same.

Back or Counter E.M.F.

When the armature of a d.c. motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence e.m.f. is induced in them as in a generator The induced e.m.f. acts in opposite direction to the applied voltage V(Lenz's law) and in known as back or counter e.m.f. Eb. The back e.m.f. Eb(= P□ □ZN/60 A) is always less than the applied voltage V, although this difference is small when the motor is running under normal conditions.



Consider a shunt wound motor shown in Fig. (4.2). When d.c. voltage V is applied across the motor terminals, the field magnets are excited and armature conductors are supplied with current. Therefore, driving torque acts on the armature which begins to rotate. As the armature rotates, back e.m.f. Eb is induced which opposes the applied voltage V. The applied voltage V has to force current through the armature against the back e.m.f. Eb. The electric work done in overcoming and causing the current to flow against Eb is converted into mechanical energy developed in the armature. It follows, therefore, that energy conversion in a d.c. motor is only possible due to the production of back e.m.f. Eb.

Net voltage across armature circuit = $V - E_b$

If R_a is the armature circuit resistance, then, $I_a = \dfrac{V - E_b}{R_a}$

Since V and Ra are usually fixed, the value of Eb will determine the current drawn by the motor. If the speed of the motor is high, then back e.m.f. Eb (= P□ ZN/60 A) is large and hence the motor will draw less armature current and viceversa.

Significance of Back E.M.F.

The presence of back e.m.f. makes the d.c. motor a self-regulating machine i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load.

$$\text{Armature current, } I_a = \frac{V - E_b}{R_a}$$

(i) When the motor is running on no load, small torque is required to overcome the friction and windage losses. Therefore, the armature current Ia is small and the back e.m.f. is nearly equal to the applied voltage.

(ii) If the motor is suddenly loaded, the first effect is to cause the armature to slow down. Therefore, the speed at which the armature conductors move through the field is reduced and hence the back e.m.f. Eb falls. The decreased back e.m.f. allows a larger current to flow through the armature and larger current means increased driving torque. Thus, the driving torque increases as the motor slows down. The motor will stop slowing down when the armature current is just sufficient to produce the increased torque required by the load.

(iii) If the load on the motor is decreased, the driving torque is momentarily in excess of the requirement so that armature is accelerated. As the armature speed increases, the back e.m.f. Eb also increases and causes the armature current Ia to decrease. The motor will stop accelerating when the armature current is just sufficient to produce the reduced torque required by the load.

It follows, therefore, that back e.m.f. in a d.c. motor regulates the flow of armature current i.e., it automatically changes the armature current to meet the load requirement.

Armature Torque of D.C. Motor

Torque is the turning moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts i.e. D.C. Motors

$$T = F \times r$$

In a d.c. motor, each conductor is acted upon by a circumferential force F at a distance r, the radius of the armature (Fig. 4.8). Therefore, each conductor exerts a torque, tending to rotate the armature. The sum of the torques due to all armature conductors is known as gross or armature torque (Ta).

Torque due to one conductor = $F \times r$ newton- metre

Total armature torque, $T_a = Z\,F\,r$ newton-metre

$$= Z\,B\,i\,\ell\,r$$

Now $i = I_a/A$, $B = \phi/a$ where a is the x-sectional area of flux path per pole at radius r. Clearly, $a = 2\pi r \ell / P$.

$$\therefore \quad T_a = Z \times \left(\frac{\phi}{2}\right) \times \left(\frac{I_a}{A}\right) \times \ell \times r$$

$$= Z \times \frac{\phi}{2\pi r \ell / P} \times \frac{I_a}{A} \times \ell \times r = \frac{Z \phi I_a P}{2\pi A} \text{ N - m}$$

or $$T_a = 0.159\, Z \phi I_a \left(\frac{P}{A}\right) \text{ N - m} \qquad \text{(i)}$$

Since Z, P and A are fixed for a given machine,

$$\therefore \quad T_a \propto \phi I_a$$

Hence torque in a d.c. motor is directly proportional to flux per pole and armature current.

(i) For a shunt motor, flux ϕ is practically constant.

$$\therefore \quad T_a \propto I_a$$

(ii) For a series motor, flux ϕ is directly proportional to armature current I_a provided magnetic saturation does not take place.

$$\therefore \quad T_a \propto I_a^2$$

Necessity of D.C. Motor Starter

At starting, when the motor is stationary, there is no back e.m.f. in the armature. Consequently, if the motor is directly switched on to the mains, the armature will draw a heavy current (Ia = V/Ra) because of small armature resistance.

As an example, 5 H.P., 220 V shunt motor has a full-load current of 20 A and an armature resistance of about 0.5 Ω. If this motor is directly switched on to supply, it would take an armature current of 220/0.5 = 440 A which is 22 times the full-load current. This high starting current may result in:

(i) burning of armature due to excessive heating effect,

(ii) damaging the commutator and brushes due to heavy sparking,

(iii) excessive voltage drop in the line to which the motor is connected. The result is that the operation of other appliances connected to the line may be impaired and in particular cases, they may refuse to work. In order to avoid excessive current at starting, a variable resistance (known as starting resistance) is inserted in series with the armature circuit. This resistance is gradually reduced as the motor gains speed (and hence Eb increases) and eventually it is cut out completely when the motor has attained full speed. The value of starting resistance is generally such that starting current is limited to 1.25 to 2 times the full-load current.

Types of D.C. Motor Starters

The stalling operation of a d.c. motor consists in the insertion of external resistance into the armature circuit to limit the starting current taken by the motor and the removal of this resistance in steps as the motor accelerates. When the motor attains the normal speed, this resistance is totally cut out of the armature circuit. It is very important and desirable to provide the starter with protective devices to enable the starter arm to return to OFF position

(i) when the supply fails, thus preventing the armature being directly across the mains when this voltage is restored. For this purpose, we use no-volt release coil.

(ii) when the motor becomes overloaded or develops a fault causing the motor to take an excessive current. For this purpose, we use overload release coil. There are two principal types of d.c. motor starters viz., three-point starter and four-point starter. As we shall see, the two types of starters differ only in the manner in which the no-volt release coil is connected.

Three-Point Starter

This type of starter is widely used for starting shunt and compound motors.

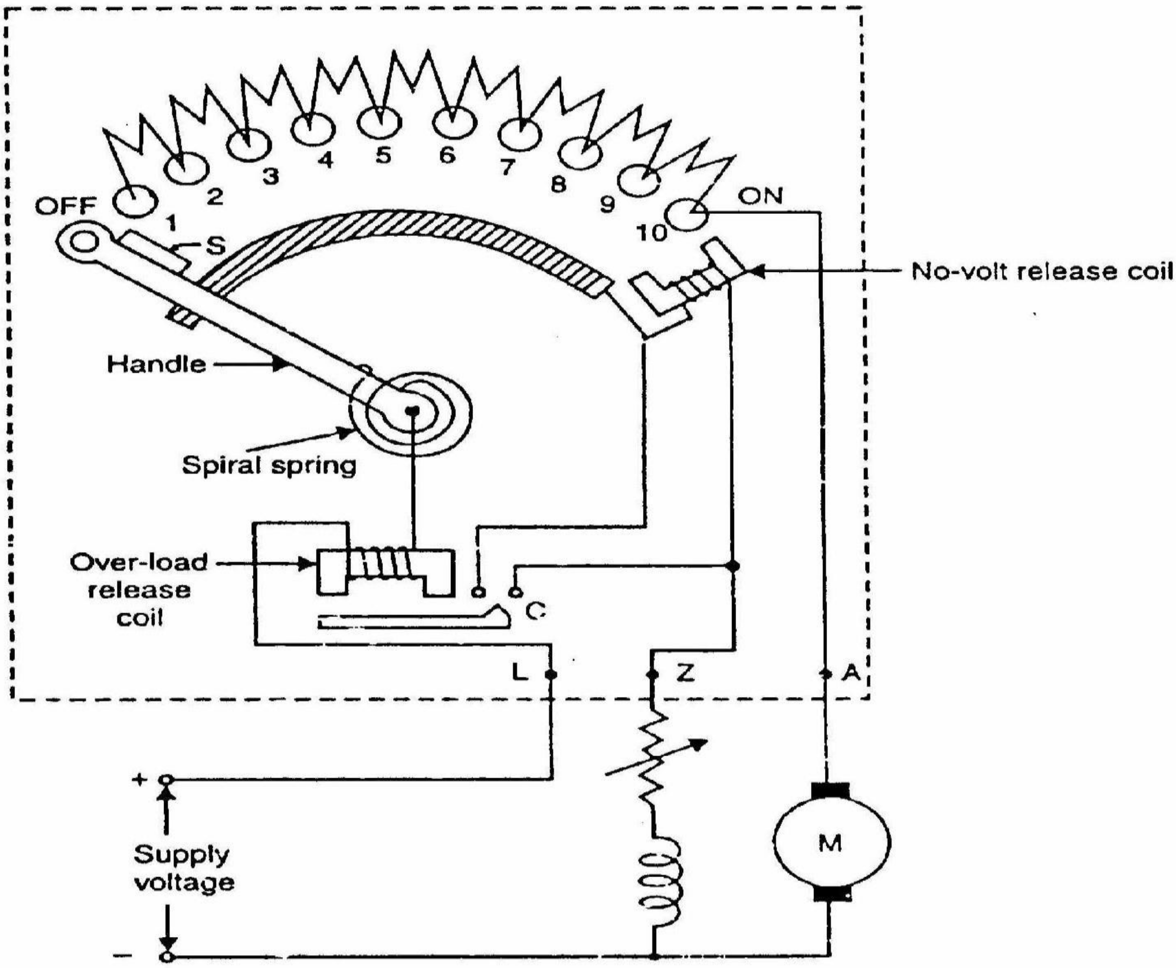
Schematic diagram

Fig. (5.16) shows the schematic diagram of a three-point starter for a shunt motor with protective devices. It is so called because it has three terminals L, Z and A. The starter consists of starting resistance divided into several sections and connected in series with the armature. The tapping points of the starting resistance are brought out to a number of studs. The three terminals L, Z and A of the starter are connected respectively to the positive line terminal, shunt field terminal and armature terminal. The other terminals of the armature and shunt field windings are connected to the negative terminal of the supply. The no-volt release coil is connected in the shunt field circuit. One end of the handle is connected to the terminal L through the over-load release coil. The other end of the handle moves against a spiral spring and makes contact with each stud during starting operation, cutting out more and more starting resistance as it passes over each stud in clockwise direction.

Operation

(i) To start with, the d.c. supply is switched on with handle in the OFF position.

(ii) The handle is now moved clockwise to the first stud. As soon as it comes in contact with the first stud, the shunt field winding is directly connected across the supply, while the whole starting resistance is inserted in series with the armature circuit.
(iii) As the handle is gradually moved over to the final stud, the starting resistance is cut out of the armature circuit in steps. The handle is now held magnetically by the no-volt release coil which is energized by shunt field current.
(iv) If the supply voltage is suddenly interrupted or if the field excitation is accidentally cut, the no-volt release coil is demagnetized and the handle goes back to the OFF position under the pull of the spring. If no-volt release coil were not used, then in case of failure of supply, the handle would remain on the final stud. If then supply is restored, the motor will be directly connected across the supply, resulting in an excessive armature current.
(v) If the motor is over-loaded (or a fault occurs), it will draw excessive current from the supply. This current will increase the ampere-turns of the over-load release coil and pull the armature C, thus short-circuiting the no-volt release coil. The no-volt coil is demagnetized and the handle is pulled to the OFF position by the spring. Thus, the motor is automatically disconnected from the supply.



Drawback

In a three-point starter, the no-volt release coil is connected in series with the shunt field circuit so that it carries the shunt field current. While exercising speed control through field regulator, the field current may be weakened to such an extent that the no-volt release coil may not be able to keep the starter arm in the ON position. This may disconnect the motor from the supply when it is not desired. This drawback is overcome in the four point starter.

Speed Control of D.C. Motors

Introduction

Although a far greater percentage of electric motors in service are a.c. motors, the d.c. motor is of considerable industrial importance. The principal advantage of a d.c. motor is that its speed can be changed over a wide range by a variety of simple methods. Such a fine speed control is generally not possible with a.c. motors. In fact, fine speed control is one of the reasons for the strong competitive position of d.c. motors in the modem industrial applications.

the various methods of-speed control of d.c. motors are:

Speed Control of D.C. Motors

The speed of a d.c. motor is given by:

$$N \propto \frac{E_b}{\phi}$$

$$N = K\frac{(V - I_a R)}{\phi} \text{ r.p.m.}$$

$$R = R_a \qquad \text{for shunt motor}$$

$$= R_a + R_{se}. \qquad \text{for series motor}$$

it is clear that there are three main methods of controlling the speed of a d.c. motor, namely:

(i) By varying the flux per pole (ϕ). This is known as flux control method.

(ii) By varying the resistance in the armature circuit. This is known as armature control method.

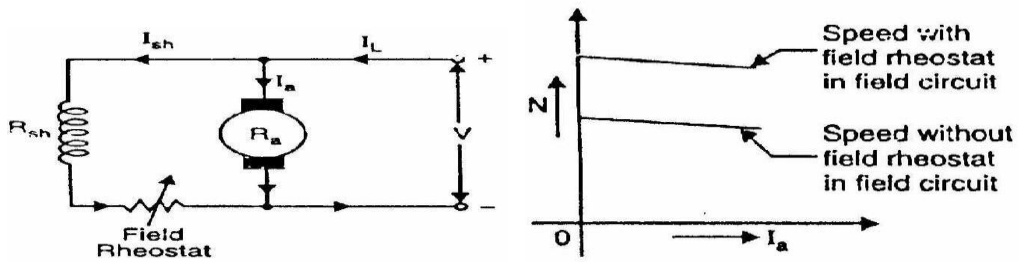
(iii) By varying the applied voltage V. This is known as voltage control method.

Speed Control of D.C. Shunt Motors

The speed of a shunt motor can be changed by (i) flux control method
(ii) armature control method (iii) voltage control method.
The first method (i.e. flux control method) is frequently used because it is simple and inexpensive.

1. Flux control method

It is based on the fact that by varying the flux ϕ, the motor speed ($N \propto 1/\phi$) canbe changed and hence the name flux control method. In this method, a variable resistance (known as shunt field rheostat) is placed in series with shunt field winding as shown in Fig.



The shunt field rheostat reduces the shunt field current Ish and hence the flux. Therefore, we can only raise the speed of the motor above the normal speed (See Fig. 5.2). Generally, this method permits to increase the speed in the ratio 3:1. Wider speed ranges tend to produce instability and poor commutation.

Advantages

(i) This is an easy and convenient method.

(ii) It is an inexpensive method since very little power is wasted in the shunt field rheostat due to relatively small value of Ish.

(iii) The speed control exercised by this method is independent of load on the machine.

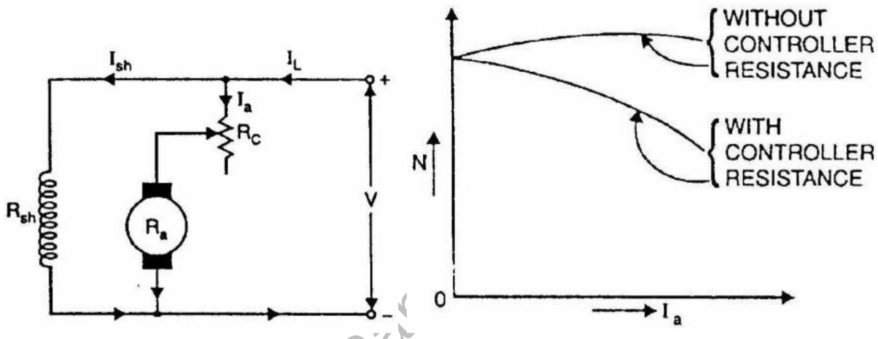
Disadvantages

(i) Only speeds higher than the normal speed can be obtained since the total field circuit resistance cannot be reduced below Rsh—the shunt field winding resistance.

(ii) There is a limit to the maximum speed obtainable by this method. It is because if the flux is too much weakened, commutation becomes poorer.

2. Armature control method

This method is based on the fact that by varying the voltage available across the armature, the back e.m.f and hence the speed of the motor can be changed. This is done by inserting a variable resistance RC (known as controller resistance) in series with the armature as shown in Fig



$$N \propto V - I_a(R_a + R_C)$$

$$R_C = \text{controller resistance}$$

Due to voltage drop in the controller resistance, the back e.m.f. (Eb) is decreased. Since N □Eb, the speed of the motor is reduced. The highest speed obtainable is lhat corresponding to RC = 0 i.e., normal speed. Hence, this method can only provide speeds below the normal speed

Disadvantages

(i) A large amount of power is wasted in the controller resistance since it carries full armature current Ia.

(ii) The speed varies widely with load since the speed depends upon the voltage drop in the controller resistance and hence on the armature current demanded by the load.

(iii) The output and efficiency of the motor are reduced.

(iv) This method results in poor speed regulation.

Due to above disadvantages, this method is seldom used to control tie speed of shunt motors.

Note. The armature control method is a very common method for the speed control of d.c. series motors. The disadvantage of poor speed regulation is not important in a series motor which is used only where varying speed service is required.

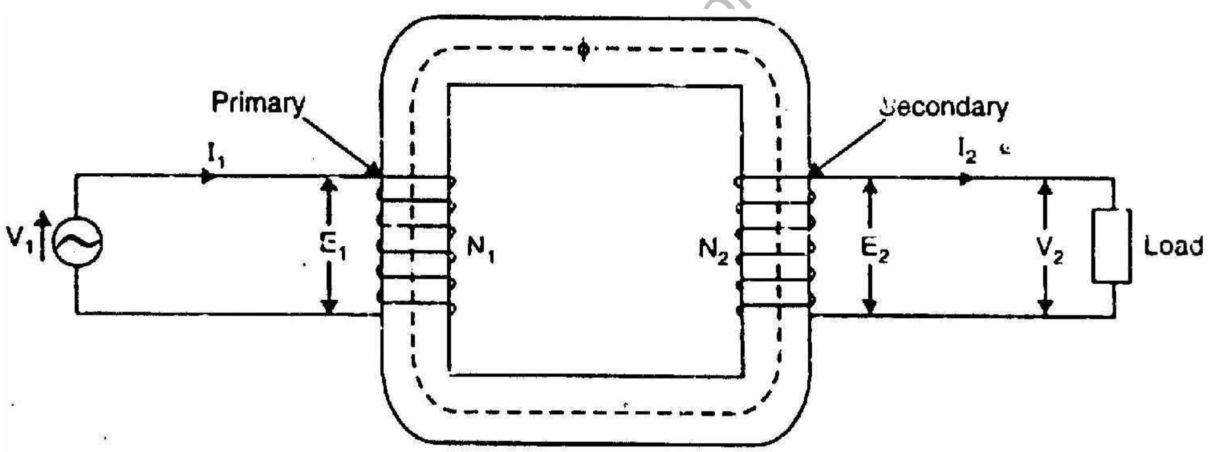
3. Transformer

Introduction

The transformer is probably one of the most useful electrical devices ever invented. It can change the magnitude of alternating voltage or current from one value to another. This useful property of transformer is mainly responsible for the widespread use of alternating currents rather than direct currents i.e., electric power is generated, transmitted and distributed in the form of alternating current. Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention. They also have a very high efficiency—as high as 99%. In this chapter, we shall study some of the basic properties of transformers.

Transformer

A transformer is a static piece of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig. . The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary). The alternating voltage V1 whose magnitude is to be changed is applied to the primary. Depending upon the number of turns of the primary (N1) and secondary (N2), an alternating e.m.f. E2 is induced in the secondary. This induced e.m.f. E2 in the secondary causes a secondary current I2. Consequently, terminal voltage V2 will appear across the load. If V2 > V1, it is called a step up-transformer. On the other hand, if V2 < V1, it is called a step-down transformer.



Working

When an alternating voltage V1 is applied to the primary, an alternating flux is set up in the core. This alternating flux links both the windings and induces e.m.f.s E1 and E2 in them according to Faraday's laws of electromagnetic induction. The e.m.f. E1 is termed as primary e.m.f. and e.m.f. E2 is termed as secondary e.m.f.

$$E_1 = -N_1 \frac{d\phi}{dt}$$

$$E_2 = -N_2 \frac{d\phi}{dt}$$

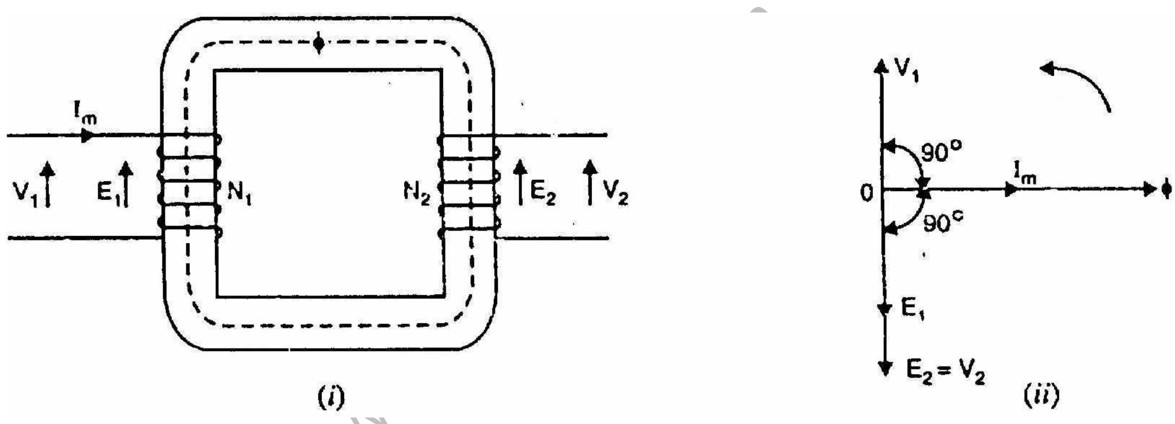
$$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Note that magnitudes of E2 and E1 depend upon the number of turns on the secondary and primary respectively. If N2 > N1, then E2 > E1 (or V2 > V1) and we get a step-up transformer. On the other hand, if N2 < N1, then E2 < E1 (or V2 < V1) and we get a step-down transformer. If load is connected across the secondary winding, the secondary e.m.f. E2 will cause a current I2 to flow through the load. Thus, a transformer enables us to transfer a.c. power from one circuit to another with a change in voltage level. The following points may be noted carefully:

(i) The transformer action is based on the laws of electromagnetic induction.
(ii) There is no electrical connection between the primary and secondary.
The a.c. power is transferred from primary to secondary through magnetic flux.
(iii) There is no change in frequency i.e., output power has the same frequency as the input power.
(iv) The losses that occur in a transformer are:
(a) core losses—eddy current and hysteresis losses
(b) copper losses—in the resistance of the windings
In practice, these losses are very small so that output power is nearly equal to the input primary power. In other words, a transformer has very high efficiency.

E.M.F. Equation of a Transformer

Consider that an alternating voltage V1 of frequency f is applied to the primary as shown in Fig. (i)). The sinusoidal flux produced by the primary can be represented as:
The instantaneous e.m.f. e1 induced in the primary is



$$e_1 = -N_1 \frac{d\phi}{dt} = -N_1 \frac{d}{dt}(\phi_m \sin \omega t)$$
$$= -\omega N_1 \phi_m \cos \omega t = -2\pi f N_1 \phi_m \cos \omega t$$
$$= 2\pi f N_1 \phi_m \sin(\omega t - 90°) \qquad \text{(i)}$$

It is clear from the above equation that maximum value of induced e.m.f. in the primary is

$$E_{m1} = 2\pi f N_1 \phi_m$$

The r.m.s. value E^ of the primary e.m.f. is

$$E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}}$$

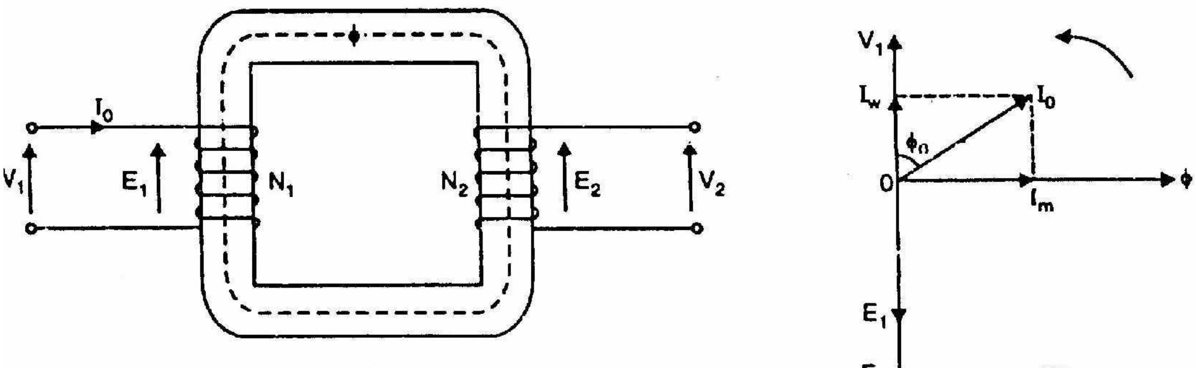
or $\qquad E_1 = 4.44 f N_1 \phi_m$

Similarly $\qquad E_2 = 4.44 f N_2 \phi_m$

In an ideal transformer, $E_1 = V_1$ and $E_2 = V_2$.

Phasor diagram.

Consider a practical transformer on no load i.e., secondary on open-circuit as shown in Fig. (i)). The primary will draw a small current I0 to supply (i) the iron losses and (ii) a very small amount of copper loss in the primary. Hence the primary no load current I0 is not 90° behind the applied voltage V1 but lags it by an angle φ0 < 90° as shown in the phasor diagram in Fig. ((ii)). No load input power, W0 = V1 I0 cos φ0

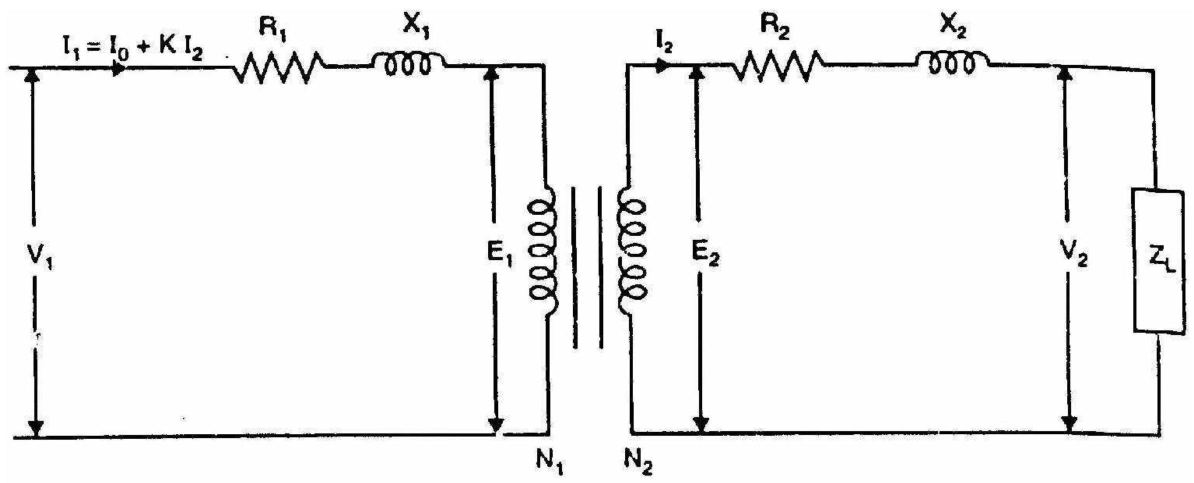


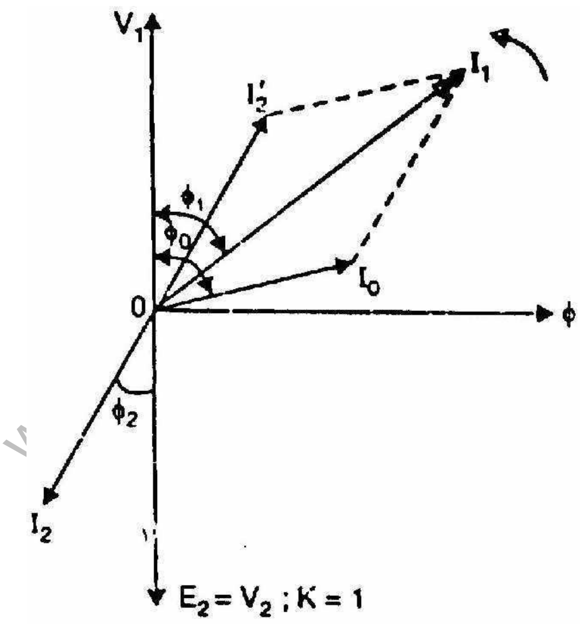
(i) (ii)

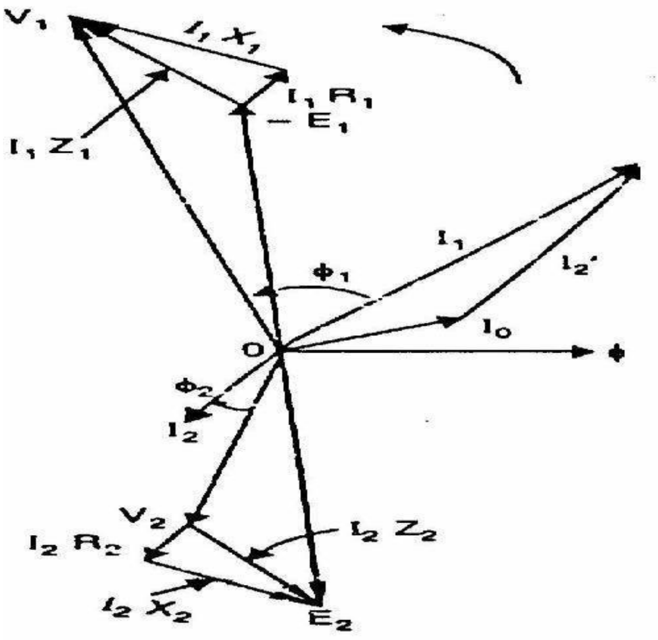
Fig. shows the phasor diagram for the usual case of inductive load.

Both E1 and E2 lag behind the mutual flux φ by 90°. The current I'2 represents the primary current to neutralize the demagnetizing effect of secondary current I2. Now I'2 = K I2 and is antiphase with I2. I0 is the no-load current of the transformer. The phasor sum of I'2 and

I0 gives the total primary current I1. Note that in drawing the phasor diagram, the value of K is assumed to be unity so that primary phasors are equal to secondary phasors.
Primary p.f. = cos □1
Secondary p.f. = cos □2
Primary input power = V1 I1 cos □1
Secondary output power = V1 I2 cos □2

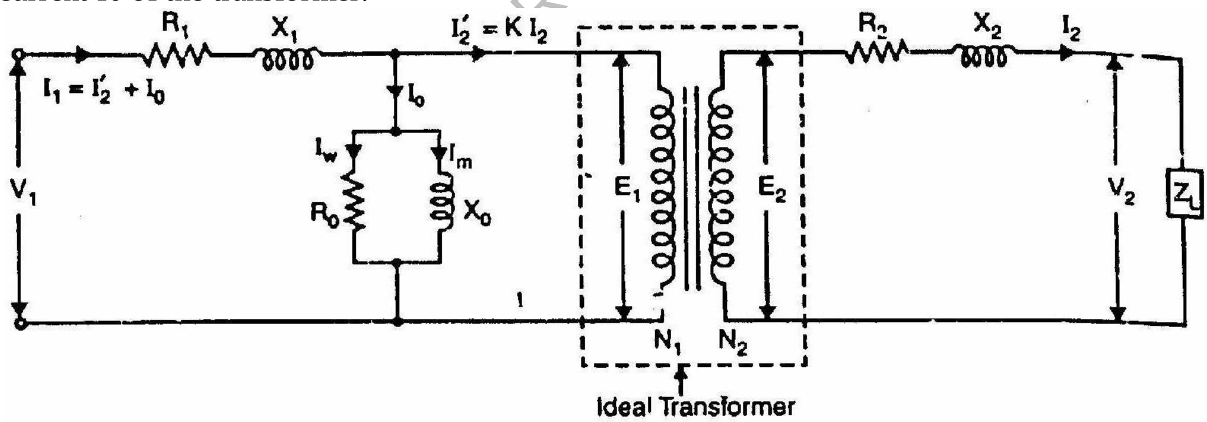






Equivalent Circuit of a Transformer

Fig shows the exact equivalent circuit of a transformer on load. Here R1 is the primary winding resistance and R2 is the secondary winding resistance. Similarly, X1 is the leakage reactance of primary winding and X2 is the leakage reactance of the secondary winding. The parallel circuit R0 X0 is the no-load equivalent circuit of the transformer. The resistance R0 represents the core losses (hysteresis and eddy current losses) so that current IW which supplies the core losses is shown passing through R0. The inductive reactance X0 represents a loss-free coil which passes the magnetizing current Im. The phasor sum of IW and Im is the no-load current I0 of the transformer.



Note that in the equivalent circuit shown in Fig. (7.19), the imperfections of the transformer have been taken into account by various circuit elements. Therefore, the transformer is now the ideal one. Note that equivalent circuit has created two normal electrical circuits separated only by an ideal transformer whose function is to change values according to the equation:

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I'_2}{I_2}$$

The following points may be noted from the equivalent circuit:

(i) When the transformer is on no-load (i.e., secondary terminals are opencircuited), there is no current in the secondary winding. However, the primary draws a small no-load current I0. The no-load primary current I0 is composed of (a) magnetizing current (Im) to create magnetic flux in the core and (b) the current IW required to supply the core losses.

(ii) When the secondary circuit of a transformer is closed through some external load ZL, the voltage E2 induced in the secondary by mutual flux will produce a secondary current I2. There will be I2 R2 and I2 X2 drops in the secondary winding so that load voltage V2 will be less than E2.

(iii) When the transformer is loaded to carry the secondary current I2, the primary current consists of two components:

(a) The no-load current I0 to provide magnetizing current and the current required to supply the core losses.

(b) The primary current I'2 (= K I2) required to supply the load connected to the secondary.

(iv) Since the transformer in Fig. in now ideal, the primary induced voltage E1 can be calculated from the relation:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

If we add I_1R_1 and I_1X_1 drops to E_1, we get the primary input voltage V_1

$$V_1 = -E_1 + I_1(R_1 + j\,X_1) = -E_1 + I_1Z_1$$

or $$V_1 = -E_1 + I_1Z_1$$

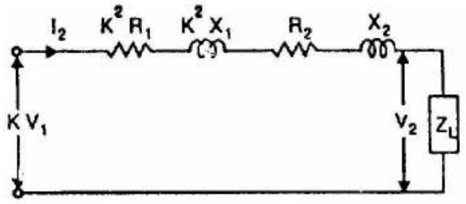
Voltage Drop in a Transformer

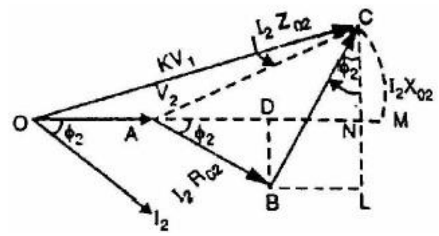
The approximate equivalent circuit of transformer referred to secondary is shown in Fig. At no-load, the secondary voltage is K V1. When a load having a lagging p.f. cos□2 is applied, the secondary carries a current I2 and voltage drops occur in (R2 + K2 R1) and (X2 + K2 X1). Consequently, the secondary voltage falls from K V1 to V2. Referring to Fig. (7.28), we have,

$$V_2 = KV_1 - I_2\left[\left(R_2 + K^2R_1\right) + j\left(X_2 + K^2X_1\right)\right]$$
$$= KV_1 - I_2\left(R_{02} + j\,X_{02}\right)$$
$$= KV_1 - V_2 = I_2Z_{02}$$

Drop in secondary voltage $= KV_1 - V_2 = I_2 Z_{02}$

The phasor diagram is shown in Fig. (7.29). It is clear from the phasor diagram that drop in secondary voltage is AC = $I_2\ Z_{02}$. It can be found as follows. With O as centre and OC as radius, draw an arc cutting OA produced at M. Then AC = AM = AN. From B, draw BD perpendicular to OA produced. Draw CN perpendicular to OM and draw BL || OM.





Approximate drop in secondary voltage

$$= AN = AD + DN$$

$$= AD + BL \qquad (\because \quad BL = DN)$$

$$= I_2 R_{02} \cos\phi_2 + I_2 X_{02} \sin\phi_2$$

For a load having a leading p.f. cos ϕ_2, we have,

$$\text{Approximate voltage drop } = I_2 R_{02} \cos\phi_2 - I_2 X_{02} \sin\phi_2$$

Note: If the circuit is referred to primary, then it can be easily established that:

$$\text{Approximate voltage drop } = I_1 R_{01} \cos\phi_2 \pm I_1 X_{01} \sin\phi_2$$

Voltage Regulation

The voltage regulation of a transformer is the arithmetic difference (not phasor difference) between the no-load secondary voltage (0V2) and the secondary voltage V2 on load expressed as percentage of no-load voltage i.e.

$$\%\text{age voltage regulation } = \frac{{}_0V_2 - V_2}{{}_0V_2} \times 100$$

$${}_0V_2 = \text{No-load secondary voltage} = K\,V_1$$
$$V_2 = \text{Secondary voltage on load}$$

$$_0V_2 - V_2 = I_2R_{02}\cos\phi_2 \pm I_2X_{02}\sin\phi_2$$

The +ve sign is for lagging p.f. and –ve sign for leading p.f.

It may be noted that %age voltage regulation of the transformer will be the same whether primary or secondary side is considered.

Transformer Tests

The circuit constants, efficiency and voltage regulation of a transformer can be determined by two simple tests (i) open-circuit test and (ii) short-circuit lest. These tests are very convenient as they provide the required information without actually loading the transformer. Further, the power required to carry out these tests is very small as compared with full-load output of the transformer. These tests consist of measuring the input voltage, current and power to the primary first with secondary open-circuited (open-circuit test) and then with the secondary short-circuited (short circuit test).

Open-Circuit or No-Load Test

This test is conducted to determine the iron losses (or core losses) and parameters R0 and X0 of the transformer. In this test, the rated voltage is applied to the primary (usually low-voltage winding) while the secondary is left opencircuited.

The applied primary voltage V1 is measured by the voltmeter, the noload current I0 by ammeter and no-load input power W0 by wattmeter as shown in Fig. (7.30 (i)). As the normal rated voltage is applied to the primary, therefore, normal iron losses will occur in the transformer core. Hence wattmeter will record the iron losses and small copper loss in the primary. Since no-load current I0 is very small (usually 2-10 % of rated current). Cu losses in the primary under no-load condition are negligible as compared with iron losses.

Hence, wattmeter reading practically gives the iron losses in the transformer. It is reminded that iron losses are the same at all loads. Fig. (7.30 (ii)) shows the equivalent circuit of transformer on no-load.

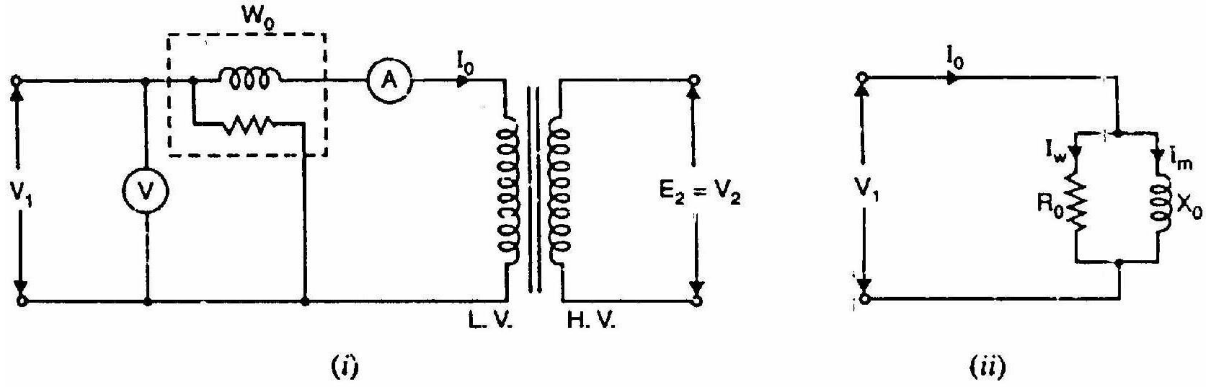
Iron losses, Pi = Wattmeter reading = W0
No load current = Ammeter reading = I0
Applied voltage = Voltmeter reading = V1
Inputpower,

$$\therefore \quad \text{No-load p.f.,}\ \cos\phi_0 = \frac{W_0}{V_1} I_0$$

$$I_W = I_0\cos\phi_0; \qquad I_m = I_0\sin\phi_0$$

$$R_0 = \frac{V_1}{I_W} \quad \text{and} \quad X_0 = \frac{V_1}{I_m}$$

Thus open-circuit test enables us to determine iron losses and parameters R0 and X0 of the transformer.

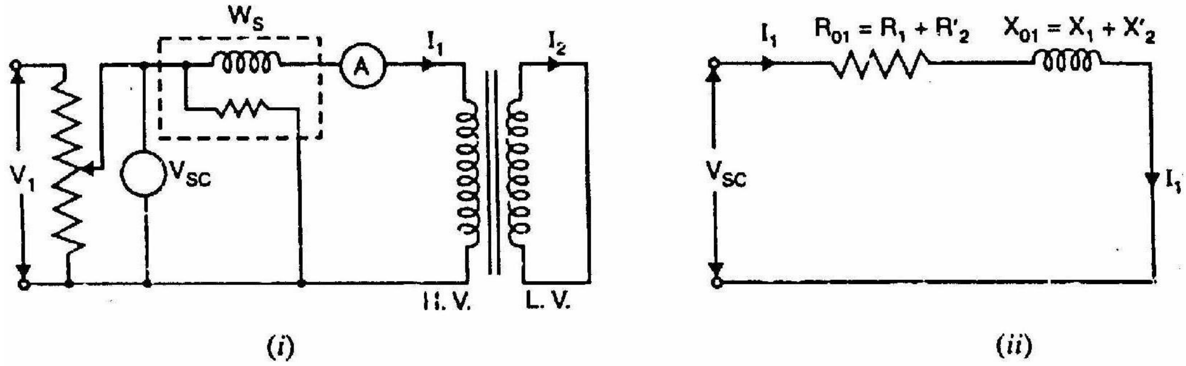


7.19 Short-Circuit or Impedance Test

This test is conducted to determine R01 (or R02), X01 (or X02) and full-load copper losses of the transformer. In this test, the secondary (usually low-voltage winding) is short-circuited by a thick conductor and variable low voltage is applied to the primary as shown in Fig. (i)). The low input voltage is gradually raised till at voltage VSC, full-load current I1 flows in the primary.

Then I2 in the secondary also has full-load value since I1/I2 = N2/N1. Under such conditions, the copper loss in the windings is the same as that on full load.

There is no output from the transformer under short-circuit conditions. Therefore, input power is all loss and this loss is almost entirely copper loss. It is because iron loss in the core is negligibly small since the voltage VSC is very small. Hence, the wattmeter will practically register the full-load copper losses in the transformer windings. Fig. (7.31 (ii)) shows the equivalent circuit of a transformer on short circuit as referred to primary; the no-load current being neglected due to its smallness.



Full load Cu loss, P_C = Wattmeter reading = W_S
Applied voltage = Voltmeter reading = V_{SC}
F.L. primary current = Ammeter reading = I_1

$$P_C = I_1^2 R_1 + I_1^2 R'_2 = I_1^2 R_{01}$$

$$\therefore \quad R_{01} = \frac{P_C}{I_1^2}$$

where R_{01} is the total resistance of transformer referred to primary.

Total impedance referred to primary, $Z_{01} = \dfrac{V_{SC}}{I_1}$

Total leakage reactance referred to primary, $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

Short-circuit p.f, $\cos\phi_2 = \dfrac{P_C}{V_{SC} I_1}$

Thus short-circuit lest gives full-load Cu loss, R_{01} and X_{01}.

Losses in a Transformer

The power losses in a transformer are of two types, namely;
1. Core or Iron losses 2. Copper losses
These losses appear in the form of heat and produce (i) an increase in temperature and (ii) a drop in efficiency.

1. Core or Iron losses (Pi)

These consist of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test. Hysteresis loss, kh $f^{1.6}$ Bm watts /m^3 Eddy current loss ke f^2 B^2 t watts/m^3

Both hysteresis and eddy current losses depend upon (i) maximum flux density Bm in the core and (ii) supply frequency f. Since transformers are connected to constant-frequency, constant voltage supply, both f and Bm are constant. Hence, core or iron losses are practically the same at all loads.

Iron or Core losses, Pi = Hysteresis loss+ Eddy current loss = Constant losses

The hysteresis loss can be minimized by using steel of high silicon content whereas eddy current loss can be reduced by using core of thin laminations.

2. Copper losses

These losses occur in both the primary and secondary windings due to their ohmic resistance. These can be determined by short-circuit test.

$$\text{Total Cu losses, } P_C = I_1^2 R_1 + I_2^2 R_2$$

$$= I_1^2 R_{01} \text{ or } I_2^2 R_{02}$$

It is clear that copper losses vary as the square of load current Thus if copper losses are 400 W at a load current of 10 A, then they will be $(1/2)^2 \times 400 = 100$ W at a load current of 5A.

$$\text{Total losses in a transformer} = P_1 + P_C$$

$$= \text{Constant losses} + \text{Variable losses}$$

It may be noted that in a transformer, copper losses account for about 90% of the total losses.

Efficiency of a Transformer

Like any other electrical machine, the efficiency of a transformer is defined as the ratio of output power (in watts or kW) to input power (watts or kW) i.e.,

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}}$$

It may appear that efficiency can be determined by directly loading the transformer and measuring the input power and output power. However, this method has the following drawbacks:

(i) Since the efficiency of a transformer is very high, even 1% error in each wattmeter (output and input) may give ridiculous results. This test, for instance, may give efficiency higher than 100%.

(ii) Since the test is performed with transformer on load, considerable amount of power is wasted. For large transformers, the cost of power alone would be considerable.

(iii) It is generally difficult to have a device that is capable of absorbing all of the output power.

(iv) The test gives no information about the proportion of various losses.

Due to these drawbacks, direct loading method is seldom used to determine the efficiency of a transformer. In practice, open-circuit and short-circuit tests are carried out to find the efficiency.

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$