

PREFACE

In a bid to standardize higher education in the country, the University Grants Commission (UGC) has introduced Choice Based Credit System (CBCS) based on five types of courses viz. *core, generic, discipline specific elective, ability and skill enhancement* for graduate students of all programmes at Honours level. This brings in the semester pattern which finds efficacy in sync with credit system, credit transfer, comprehensive continuous assessments and a graded pattern of evaluation. The objective is to offer learners ample flexibility to choose from a wide gamut of courses, as also to provide them lateral mobility between various educational institutions in the country where they can carry their acquired credits. I am happy to note that the university has been recently accredited by National Assessment and Accreditation Council of India (NAAC) with grade “A”.

UGC (Open and Distance Learning Programmes and Online Programmes) Regulations, 2020 have mandated compliance with CBCS for U.G. programmes for all the HEIs in this mode. Welcoming this paradigm shift in higher education, Netaji Subhas Open University (NSOU) has resolved to adopt CBCS from the academic session 2021-22 at the Under Graduate Degree Programme level. The present syllabus, framed in the spirit of syllabi recommended by UGC, lays due stress on all aspects envisaged in the curricular framework of the apex body on higher education. It will be imparted to learners over the six semesters of the Programme.

Self Learning Material (SLMs) are the mainstay of Student Support Services (SSS) of an Open University. From a logistic point of view, NSOU has embarked upon CBCS presently with SLMs in English / Bengali. Eventually, the English version SLMs will be translated into Bengali too, for the benefit of learners. As always, all of our teaching faculties contributed in this process. In addition to this we have also requisitioned the services of best academics in each domain in preparation of the new SLMs. I am sure they will be of commendable academic support. We look forward to proactive feedback from all stakeholders who will participate in the teaching-learning based on these study materials. It has been a very challenging task well executed, and I congratulate all concerned in the preparation of these SLMs.

I wish the venture a grand success.

Professor (Dr.) Subha Sankar Sarkar
Vice-Chancellor

NETAJI SUBHAS OPEN UNIVERSITY
Under Graduate Degree Programme
Choice Based Credit System (CBCS)
Subject : Honours in Physics (HPH)
Course : Electrical Circuits and Network Skills
Course Code: SE-PH-11

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**NETAJI SUBHAS
OPEN UNIVERSITY**

**UG : Physics
(HPH)**

Course : Electrical Circuits and Network Skills

Course Code : SE-PH-11

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Unit 1 □ Basic Electricity Principle

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 - 1.4.1 AC Electricity**
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1.0 Objective

By going through this chapter, you will learn following topics

- About voltage, current and resistance in a circuit
- About combination of resistances
- Power loss in resistance in a circuit
- Types of Current
- Measurements of Voltage, current and resistance.

1.1 Introduction

In everyday life we are familiar with voltage, current, resistances and power in some way or other. Knowledge of the combination of resistances is important. It is also essential to know about ammeter and voltmeter and the working principle of multi meter.

1.2 Voltage, current, resistance and power

Voltage: The work done per unit positive charge in moving it through two points in a conductor is known as the potential difference or voltage between the points. The charge flows in a conductor in the decreasing potential. Hence the potential difference is

$$V = V_1 - V_2 = -\int_2^1 \vec{E} \cdot d\vec{l} = \int_1^2 \vec{E} \cdot d\vec{l} \quad 1.2.1$$

E is the electric field. Now the current density

$$\vec{J} = \sigma \vec{E} \text{ or, } \vec{E} = \rho \vec{J} \quad 1.2.2$$

Here σ is the conductivity and ρ is the resistivity of the material of a conductor. Therefore

$$V = \int \rho \vec{J} dl = \int \frac{\rho I}{A} dl = IR \quad 1.2.3$$

Here I is the current flowing through a conductor of length L and cross-section area A

Current:

In an isolated metallic conductor, the free electrons present in it are in random motion and the net rate at which electrons pass through any hypothetical plane is zero. If the ends of the conductor are connected to a battery, an electric field \vec{E} will be developed at every point within the conductor. This field will act on electrons and will give them a resultant motion in the direction of \vec{E} . The flow of electrons will constitute an electric current which is defined as the rate at which charges pass through any specified surface area. Thus

$$I = \frac{Q}{t}, \quad 1.2.4$$

where Q is the net charge moving in time t . At any instant of time if dq amount of charge passes through any given cross section in time dt then the electric current is defined as

$$i = \frac{dq}{dt} \quad 1.2.5$$

In SI system, the unit of current is Ampere. It is also the practical unit of current.

The current may be due to flow of both positive and negative charges. In metals charge carriers are negatively charged free electrons. In semiconductors charge carriers are both electrons and holes.

Current Density:

For the microscopic description of flow of charges in a medium, the idea of current density (\vec{J}) is introduced. It is a vector \vec{J} and is a characteristic of a point inside a conductor. It is defined as the current per unit area through an infinitesimal area normal to the direction of current flow.

Unit- Amp/m².

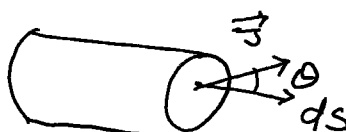


Fig 1.2.1

Current is the flux associated with \vec{J} and is a scalar quantity. Current is not a vector quantity as it does not obey the vector law of addition. The arrow associated with the current in a conductor shows the direction of charge flow. Direction of flow of positive charges is taken as the direction of current.

Resistance:

The resistance is the property of a substance due to which it opposes the flow of current through it. The resistance of a conductor depends a) directly on its length l , b) inversely as the area of cross section A of the conductor, c) on the nature of the material of the conductor. Thus



Fig 1.2.2

$$R = \rho l/A \tag{1.2.6}$$

Where ρ is a constant and it depends upon the nature of the material of the conductor and is known as specific resistance or resistivity.

Practical unit of resistance is Ohm.

A conductor which is characterised by its resistance only is known as a Resistor.

Power: When a charge dq moves through a potential difference V the work done by the potential source is $dW = Vdq$. The power P is defined as the rate of doing work. Thus

$$P = \frac{dW}{dt} = \frac{Vdq}{dt} = VI = I^2R = \frac{V^2}{R} \tag{1.2.7}$$

where I is the current through the resistor R . The power is dissipated in the form of Joule heat.

Unit of power is Watt, when I is expressed in Ampere and V is in volt.

1.3 Ohm's law

Provided temperature and other physical conditions remain constant, the ratio of potential difference V between any two points on a conductor is proportional to the current I flowing between these points (A and B) is constant. Mathematically,

$$V/I = \text{constant.}$$

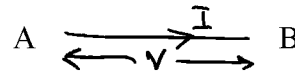


Fig 1.3.1

For a straight conductor of uniform cross section, whose end points are kept at a potential difference V the current through the conductor is given by Ohm's law. In $V/I = \text{constant}$ $V = IR$, where R is the resistance of the conductor and this is constant when temperature is constant.

Ohm's law applies to linear devices such as conductors. It does not apply to nonlinear devices such as diodes, transistors etc.

1.3.1 Series, Parallel and Series-parallel Combination

Series combination:

When the conductors having resistances R_1, R_2, \dots , are joined end to end then it is called series combination. The equivalent resistance between the starting and end point is equal to the sum of the individual resistances.

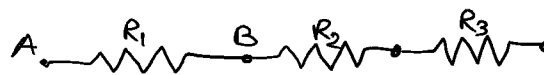


Fig 1.3.2

Proof: Let us consider three resistances between the points A and D. If a voltage V is applied across these points. Then

- i) Current is same through all the resistances.
- ii) The voltage drop across each resistance is given by Ohm's law. Thus

$$V_B - V_A = IR_1$$

$$V_C - V_B = IR_2$$

$$V_D - V_C = IR_3$$

Therefore,

$$V_D - V_A = I(R_1 + R_2 + R_3) \quad 1.3.1$$

Now, if a resistance R is kept in between the points A and D , then

$$V_D - V_A = IR \quad 1.3.2$$

Here R is the equivalent resistance between A and D . Comparing 8 and 9,

$$R = (R_1 + R_2 + R_3) \quad 1.3.3$$

Parallel combination:

Here the resistances are so connected that the potential drop $V_A - V_B$ across each resistance is same. Let us consider three resistances R_1, R_2, R_3 are connected in parallel combination as in the fig 2 below.

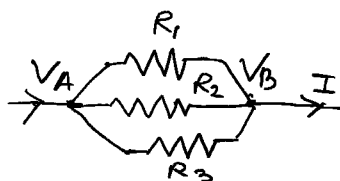


Fig 1.3.3

According to Kirchhoff's law

$$I = I_1 + I_2 + I_3$$

where I_1, I_2 and I_3 are currents through R_1, R_2 and R_3 respectively. Then

$$I_1 = \frac{V_B - V_A}{R_1}$$

$$I_2 = \frac{V_B - V_A}{R_2} \quad \text{and} \quad 1.3.4$$

$$I_3 = \frac{V_B - V_A}{R_3}$$

$$I = I_1 + I_2 + I_3 = (V_B - V_A) \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) \quad 1.3.5$$

If instead of R_1, R_2, R_3 a resistance R is placed between A and B , then

$$I = \frac{(V_B - V_A)}{R} \quad 1.3.6$$

Comparing eqn. 1.2.5 and 1.2.6 we get

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad 1.3.7$$

Here R is called the equivalent resistance between R_1 , R_2 and R_3

Series-parallel combination:

When a no. of resistances R_1, R_2, R_3, \dots are connected in series with the parallel combination of no of resistances R_1, R_2, R_C, \dots the the equivalent resistance of the series parallel combination will be

$$R_{SP} = (R_1 + R_2 + R_3 + \dots) + \left(\frac{1}{R_A} + \frac{1}{R_B} + \frac{1}{R_C} + \dots \right) \quad 1.3.8$$

Equivalent resistance:

The equivalent resistance of a circuit (or network) between any two points (or terminal) is given by a single resistance which will replace the entire given circuit between these two points. It is usually found using series and parallel combination laws of resistances.

1.4 AC Electricity and DC Electricity

1.4.1 AC Electricity

An alternating current or voltage is one which passes through a complete cycle of changes both in magnitude and direction at regular intervals of time. The variation is usually sinusoidal in type. Even if the current or voltage varies in a non sinusoidal arbitrary periodic manner, it can be considered as the superposition of a number of sinusoidal variations. AC voltage may be generated by rotating a coil in a uniform magnetic field. The general expression of sinusoidal voltage or current is

$$v = v_0 \sin \omega t \text{ or } i = i_0 \sin \omega t \quad 1.4.1$$

Generally the voltage is written as

$$v = v_0 \sin (\omega t + \alpha) \quad 1.4.1a$$

where v_0 is the peak value or the amplitude, ω is the angular frequency and α is the phase angle of the instantaneous voltage v with respect to the reference $v_t = v_0 \sin \omega t$. The time period T is given by

$$T = \frac{2\pi}{\omega} \text{ and frequency } f = \frac{1}{T} = \frac{\omega}{2\pi}.$$

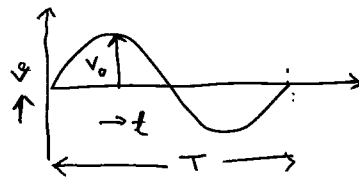


Fig 1.4.1: Representation of sinusoidal AC voltage

The circuit diagram for a sinusoidal voltage across a resistance is shown below.

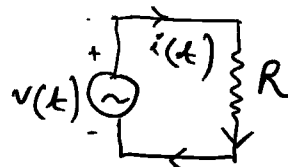


Fig 1.4.2

When an alternating voltage is applied to a circuit the current in the circuit also varies with time at the frequency of applied voltage. Such current is represented as

$$i = I_0 \sin (\omega i + \varphi) \tag{1.4.2}$$

where, I_0 is the peak current and φ is the phase difference between current and voltage.

Average or mean value:

The average of an alternating waveform with period T over a complete cycle is zero. Thus in this case average means average over a half cycle. The average current may be defined as the dc equivalent of current which causes the same amount of charge flow in half time period as is caused by the ac during a half cycle. Thus,

$$V = \int \rho \vec{J} dl = \int \frac{\rho I}{A} dl = IR \tag{1.4.3}$$

$$V_{av} = \frac{1}{T/2} \int_0^{T/2} v(t) dt = \frac{2V_0}{\pi} \tag{1.4.3a}$$

Root mean square (r.m.s) or effective value:

Since the mean value of alternating waveform over a complete cycle is zero, the root mean square value is defined. The root mean square value (rms) or effective value of an alternating current is defined as

$$I_{rms} = \sqrt{\frac{1}{T} \int_0^T i^2(t) dt} \quad 1.4.4$$

The heat produced by AC in a resistance R over a time period T is

$$\int_0^T i^2(t).R dt = I_{rms}^2 RT.$$

Thus the rms value may be defined as the equivalent of direct current which produces the same heating effect as is caused by the ac during one time period. If

$$i = I_0 \sin \omega t$$

$$I_{rms}^2 = \frac{1}{T} \int_0^T I_0^2 \sin^2 \omega t dt$$

$$I_0^2 / 2T \int_0^T (1 - \cos \omega t) dt = \frac{I_0^2}{2}$$

Therefore,

$$I_{rms} = \frac{I_0}{\sqrt{2}} \quad 1.4.4a$$

Measuring instruments based on heating effect of ac are generally calibrated in terms of rms value.

Q. Why 220 V AC supply is more dangerous than 220 V DC supply?

Form Factor:

The form factor gives an idea of the wave shape of the ac supply. It is defined as the ratio of rms value of ac to the average value. Thus

$$k_f = \frac{I_{rms}}{I_{av}} = \frac{\frac{I_0}{\sqrt{2}}}{2I_0/\pi} = 1.11 \quad 1.4.5$$

Deviation from the value 1.11 gives deviation from sinusoidal wave.

1.4.2 DC Electricity

When current or voltage does not change with time, it is known as DC electricity or steady current.

Equation of Continuity:

Let us consider a volume V enclosed by a surface S . Let \vec{J} be the current density at any surface element $d\vec{s}$, then the current flowing through S is

$$I = \int \vec{J} \cdot d\vec{s} \quad 1.4.6$$

If ρ be the charge density at any volume element dV , then total charge within V is

$$q = \int \rho \, dV \quad 1.4.7$$

From local conservation of charge

$$\int J \cdot ds = -\frac{dq}{dt} = -\int \frac{\partial \rho}{\partial t} \, dV \quad 1.4.8$$

Since eqn 1.3.8 is true for any volume element V ,

$$\therefore \vec{\nabla} \cdot \vec{J} + \frac{\partial \rho}{\partial t} = 0 \quad 1.4.8a$$

Equation 1.3.8a is known as equation of Continuity. It relates charge density ρ at a point to the current density \vec{J} at that point. When ρ is constant, which is the case of steady current flow

$$\frac{\partial \rho}{\partial t} = 0 \quad \text{and} \quad \vec{\nabla} \cdot \vec{J} = 0 \quad 1.4.8b$$

Or in other words,

$$\int \vec{J} \cdot d\vec{s} = 0 \quad 1.4.9$$

Therefore for steady current flow, there cannot be any accumulation of charge anywhere. Since $\vec{J} = \sigma \vec{E}$, which is Ohm's law we have from eqn 1.3.9

$$\vec{\nabla} \cdot \vec{E} = 0 \quad 1.4.9b$$

Again from $\vec{\nabla} \times \vec{E} = 0$, and $\vec{E} = -\vec{\nabla} \phi$, where ϕ is scalar potential, from eqn 1.4.9b

$$\nabla^2 \phi = 0 \quad 1.4.9c$$

This is Laplace equation. When solution of Laplace eqn is known, \vec{E} is determined from $\vec{E} = -\vec{\nabla}\phi$ and hence \vec{J} is determined from the relation $\vec{J} = \sigma\vec{E}$.

Kirchhoff's law and Network analysis:

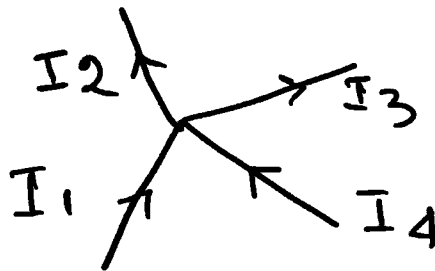
1. Kirchhoff's current law (KCL):

The algebraic sum of the currents meeting at a junction point in a network is zero. Mathematically

$$\Sigma I_k = 0 \quad 1.4.10$$

If current entering a junction is taken as positive then the current leaving the junction should be negative. Thus for the following figure

$$I_1 - I_2 - I_3 + I_4 = 0 \quad 1.4.10a$$



$$I_1 - I_2 - I_3 + I_4 = 0$$

Fig 1.4.3

This law is a consequence of the conservation of charge.

2. Voltage law (KVL):

The algebraic sum of the products of current and resistance in each part of any loop in a network is equal to the algebraic sum of the electromotive forces in the same loop. Mathematically

$$\Sigma I_k R_k = \Sigma E_k, \quad 1.4.11$$

where R_k is the resistance in the k th branch of the loop, and I_k is the current through it and E_k is the emf in the circuit.

Example:

Let us consider the fig which shows one of the loops of a complex network.

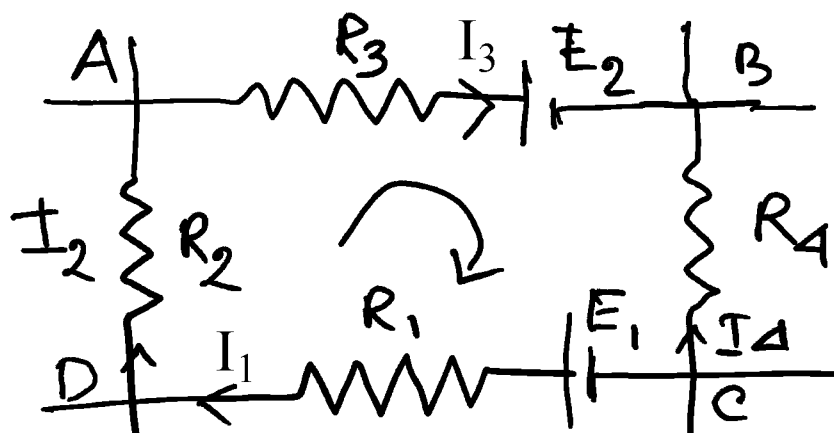


Fig 1.4.4

When we start from a point A and goes clockwise the current eqn will be

$$I_3 R_3 - I_4 R_4 + I_1 R_1 + I_2 R_2 = 0 \quad 1.4.11a$$

And

$$E_1 - E_2 = 0 \quad 1.4.11b$$

E_1 is taken positive since it sends current in the direction shown and E_2 is taken negative since it sends current in the opposite direction.

Thevenin's theorem:

In a linear network containing emf source, resistance and load, sometimes Thevenin's theorem is very useful. It states that in a circuit containing linear Ohmic resistances and voltage sources the current flowing through a load resistance will be same as that supplied by a single open circuit voltage source V_g and internal resistance R_g . V_g is the open circuit voltage across the terminals of the load and R_g is the resistance of the circuit looking from these terminals with all energy sources replaced by their internal resistances. V_g is called open circuit voltage or **Thevenin's voltage** and R_g is called **Thevenin's resistance**.

Let a battery of emf V_B and internal resistance R_i is connected across the terminals A and B. A load resistance R_L is connected across the terminals C and D. Let i_1 be the current flowing through the resistances R_i and R_1 and i_2 be the current flowing through the resistances R_2 and R_L . Then the current flowing through R_3 is $i_1 - i_2$. Applying KVL in loop 1, we get

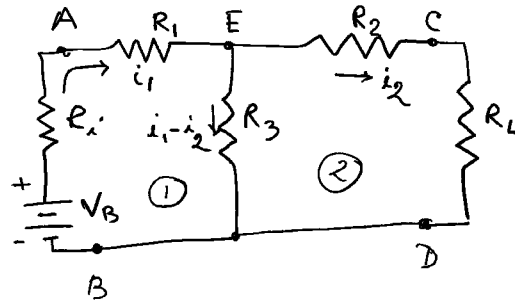


Fig 1.4.5

$$-V_B + (R_i + R_1)i_1 + R_3(i_1 - i_2) = 0 \quad 1.4.12$$

And for loop 2 we get

$$-R_3((i_1 - i_2)) + (R_2 + R_L)i_2 = 0 \quad 1.4.13$$

After rearranging eqn 1.3.12 and 1.3.13 and solving for load current i_2 by Cramer's rule, we get

$$i_2 = \frac{R_3 V_B}{(R_L + R_2)(R_i + R_3 + R_1) + R_3(R_1 + R_i)} \quad 1.4.14$$

When the load is disconnected the circuit will reduce to that of the fig 1.3.6 shown below. The current through R_2 being zero, the voltage V_g is the voltage develop across R_3 which is

$$V_g = iR_3 = \frac{V_B}{R_i + R_1 + R_3} \cdot R_3 \quad 1.4.15$$

Open circuit voltage V_g :

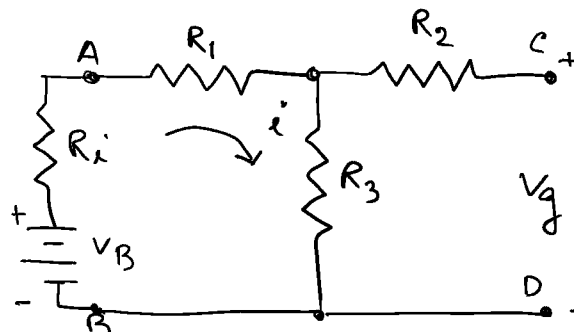


Fig 1.4.6

Now the battery is replaced by its internal resistance R_i . From the fig.1.3.7 R_g is the resistance across the terminals CD. It is the series combination of R_2 with R_3 and $(R_1 + R_i)$ in parallel.

Determination of R_g :

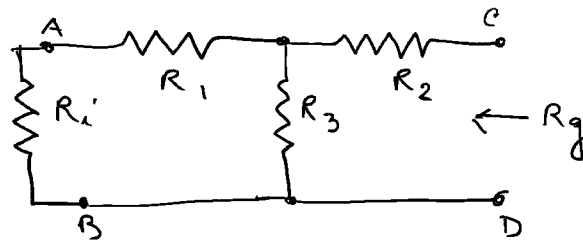


Fig 1.4.7

$$R_g = R_2 + \frac{R_3(R_1 + R_i)}{R_3 + R_1 + R_i} \tag{1.4.16}$$

Now if R_L is connected across a voltage source V_g and internal resistance R_g , then the current through the load R_L is given by

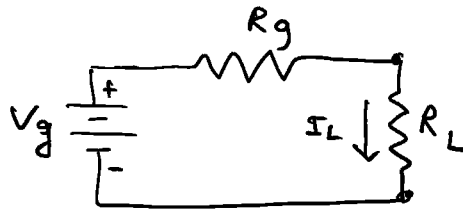


Fig 1.4.8 Equivalent Thevenin circuit

$$i_L = \frac{V_g}{R_g + R_L} = \frac{R_3 B_B}{(R_L + R_2)(R_1 + R_3 + R_i) + R_3(R_1 + R_i)} \tag{1.4.17}$$

It is seen that i_L is the same current as was solved before for i_2 (equation 1.4.14). This establishes Thevenin's theorem.

1.5 Familiarisation with Multimeter

Multimeter is an electrical measuring instrument that combines several measurement functions in a single entity. It can measure voltage (AC, DC), current and resistances. It is also known as VOM (Volt-Ohm-Milliammeter). Nowadays

multimeter can also measure capacitance, transistor's current gain, inductance, temperature, etc. Analog multimeter uses a micro ammeter with a moving pointer to display readings. Digital multimeter has a numeric display. Though digital multimeters have lower cost and greater precision, analog multimeters are still preferable in some cases.



Fig 1.5.1

Parts of a Multimeter:

A multimeter has three parts:

1. Display: The display usually has 4 digits and it also can display a negative sign.

2. Selection knob: The selection knob can be used to set the multimeter to read milliamps of current (mA), voltage (V), resistance (R) etc.

3. Ports: There are three ports on the front of the unit. COM stands for common and is almost always connected to Ground or '–' of a circuit. Two probes are plugged into two of the ports. The COM port is conventionally black but there is no difference between the red probe and the black probe other than colour. 10A port is special port used when measuring large currents (greater than 200mA). mA/V is the port where the red probe is conveniently plugged in. This port allows the measurement of current (upto 200mA), Voltage (V), and resistance (R). The probes have banana type connector on the end that plugs into the multimeter. Different types of probes available for multimeter are

1. Banana to alligator clips:

2. Banana to IC hooks
3. Banana to Tweezers
4. Banana to test probes.

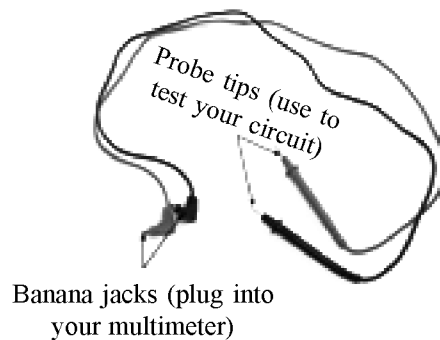


Fig 1.5.2

Measuring a Voltage:

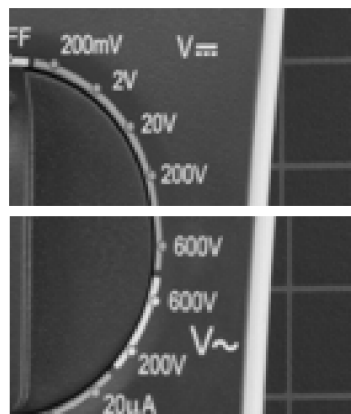


Fig 1.5.3

For measuring voltage on a battery or between two points in a circuit, the black probe is plugged into COM and the red probe into mA. The multimeter knob is set to '2V' say, in the DC (direct current) range (V with straight line is used to measure DC voltage and V with wavy line is used to measure AC voltage). The black probe is connected to batteries ground or '- ' and the red probe to '+ '. The voltage of the battery will be displayed on the screen. If the red and black probes are interchanged the reading on the multimeter is simply negative.

Overload: When we select a voltage setting that is too low for the voltage we are trying to measure the meter will simply display 1. It means it is overloaded or out of range condition. In this case the multimeter knob is to be changed to the next highest settings.

Measuring resistances:

Though normal resistors have colour codes on them but if one does not know what they mean, a multimeter is very useful in measuring resistances. Let us take a resistor and set the multimeter at 20K setting. Then hold the probe against the resistor legs. The meter will read one of three values, 0.00, 1, or the actual resistor value.

If the meter reads .97, it means the resistor has a value of 970 since 20K range is chosen. So we need to move the decimal to three places to the right.

If the meter reads 1 or displays oL, it's overloaded and the range knob is to be adjusted to a higher mode such as 200K mode or 2M (Mega Ohm) mode.

But if the meter reads 0.00, or nearly zero, then the knob is to be fixed in lower mode to 2 K or 200. Since many resistances have 5% tolerance, though colour code may indicate 10,000 ohm, the multimeter may read it as 10.5 K or 9.5 K.

Note: Measuring resistance is not perfect. Temperature and also surrounding components on a circuit board may affect the reading.

Measurement of current:

To measure the current one has to physically interrupt the circuit to put the meter inline. We now set the selection knob to the proper setting and measure current by choosing current range. Let us set the meter to 200 mA; the red probe is kept in the port mA/V port. Thus same port is used to measure current, voltage or resistance. To be safe it is desirable to switch the knob to a higher range side than the current range we are to measure. In the case of current measurement, overloading the current can result in a blown fuse rather than just a overload display.

When the meter is added to the circuit in series, the meter will display instantaneous current reading. Readings may fluctuate and all multimeter take readings over time and then gives the average. If the colour of the probe is interchanged, it simply causes the current reading to become negative.

Continuity:

This test helps us to ensure that connections are made correctly between the two points and also to detect if two points are connected that should not be. Continuity testing is the testing of resistance between two points. When there is very low resistance (less than a few ohms) the two points are connected electrically and a tone is heard. If there is more than a few ohm resistances, the circuit is open and no tone is heard.

To test the continuity the multimeter is at first set into continuity mode (a diode symbol with propagation waves around it). Now the probes are touched together. The meter should emit a note. This is continuity setting. Next the probes are used in the circuit between the points to check the continuity. When a system is not working the continuity checking helps to trouble shoot the system.



Fig 1.5.4

NOTE: There is some significant amount of capacitance in the power system. Capacitance will act like a short for a moment until they are fully charged and then acts as an open circuit. Thus if one hear a short beep and then nothing, then it is of no problem. The capacitors are charging up.

1.6 Voltmeter and Ammeter

The ordinary ammeters and voltmeters are merely pivot galvanometers. In pivot galvanometer, the moving coil, instead of being suspended is pivoted between two jewel bearings. These galvanometers are portable and are very useful.

Voltmeter:

When a galvanometer is used as a voltmeter, its resistances must be much larger than any resistance across which it is to be placed. If not the insertion of voltmeter will decrease the current flow in the circuit and the p.d measured will be smaller than the actual value. Here the galvanometer resistance R_g is increased using many turns of fine wire. A high resistance R is used in series with the galvanometer to increase the total resistance. If I_g is the total current through the galvanometer for full scale deflection D , then

$$i_g(R + R_g) = V \quad 1.6.1$$

$$\text{Or,} \quad R = \frac{V}{I_g} - R_g \quad 1.6.1a$$

For ideal case, $R \rightarrow \infty$

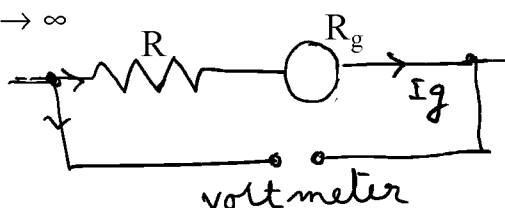


Fig 1.6.1

Ammeter:

When the galvanometer is used as ammeter or current measuring instrument, its resistance is desirable to be very low compared with the total resistance in the circuit, so that when the galvanometer is placed in series with the circuit, the current in the circuit should not alter. For this purpose a low resistance shunt S is connected in parallel to the galvanometer. If I_g is the total current through the galvanometer for full scale deflection, then the resistance S is adjusted in such a way that $I - I_g$ passes through the shunt. In such situation, potential across the shunt is equal to the potential across the galvanometer coil, or

$$S(I - I_g) = I_g R_g \quad 1.6.2$$

R_g is galvanometer resistance. Or

$$S = \frac{I_g}{I - I_g} R_g \quad 1.6.2a$$

For ideal case; $S \rightarrow 0$.

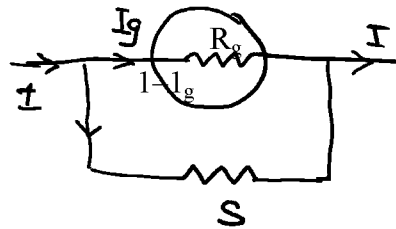


Fig 1.6.2

Shunts and Multipliers:

Shunt is the resistance used in parallel with a galvanometer to convert it to an ammeter and to increase the range of the instrument to a given ratio.

Multiplier is the resistance used in series with a galvanometer to convert it to a voltmeter.

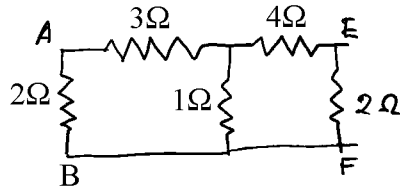
1.7 Summary

Resistance is everywhere. The loss or drop of voltage depends on resistance and its combination. The current and voltage can be measured by instrument called ammeter and voltmeter. Nowadays a combined instrument developed using advance electronics to measure current, voltage, resistance and relevant parameter in one instrument called multimeter.

1.8 Short questions and problems

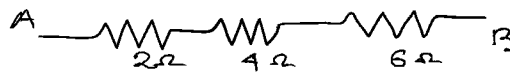
1. Define voltage, current and power in an electrical circuit.
2. What is Ohm's law?
3. What is AC electricity and what is DC electricity? Which is more dangerous 220 V ac or 220 V dc?
4. State Thevenin and Norton theorems in electrical circuit.
5. How multimeter can check continuity in a circuit?
6. How can you convert a galvanometer to a voltmeter or to an ammeter?

7. Find the equivalent resistance between the points A and B of the circuit given below.



$$\text{Ans.} = \frac{54}{41} \Omega$$

8. Find the voltage drop across each resistor, when a 24 V battery is connected across the series combination of three resistances 2, 4 and 6 Ohms.



$$\text{Ans. } \begin{aligned} V_1 &= 4V \\ V_2 &= 8V \\ V_3 &= 12V \end{aligned}$$

9. A milli ammeter with Full scale deflection (FSD) = 5 mA has a resistance of 15 ohm. Find shunt resistance necessary to convert the meter to one having FSD = 1 amp.
10. A milli ammeter with FSD = 100 micro amp has a resistance of 750 Ohm. Find the resistance of the multiplier necessary to use the instrument as a voltmeter reading 0.5V

Unit 2 □ Understanding Electrical Circuits

Structure

- 2.0 Objective**
- 2.1 Introduction**
- 2.2 Main electric circuit elements and their Combinations**
- 2.3 Rules to analyse DC sourced electrical circuit**
- 2.4 Current and Voltage drop across the DC circuit elements**
 - 2.4.1 Superposition Theorem**
 - 2.4.2 Norton's Theorem**
 - 2.4.3 Maximum Power transfer Theorem**
- 2.5 Single phase and three phase alternating current Sources**
 - 2.5.1 Single phase**
 - 2.5.2 Three phase alternating current Sources**
- 2.6 Rules to analyse AC sourced electrical circuits**
- 2.7 Real Imaginary and Complex power**
- 2.8 Components of AC Source**
- 2.9 Saving energy and Money**
- 2.10 Summary**
- 2.11 Short questions**

2.0 Objective

By going through this chapter, you will learn following topics

- About Inductance, capacitance, and their application in a circuit.
- Network theorems related to Dc circuit.
- AC circuit analysis
- Power factor and saving of energy.

2.1 Introduction

In electrical circuits there are circuit elements which may be in single use or may be used in combination of two or more such similar elements. Electrical circuits may not be simple. They are analysed using some important network theorems.

2.2 Main electric circuit elements and their Combinations

These are resistors, capacitors and inductors. These are simple circuit elements. They have only two terminals to connect to other components and hence called one port elements. Since these elements do not give a source of energy, they are called passive elements. The current voltage relation in these elements is linear function and hence they are called linear circuit elements.

Practically these elements are not ideal or pure. A resistor may have capacitance between its ends and a small series inductance which is extremely small for non inductive winding of the resistor. Similarly a inductance coil may have small resistance. A capacitor has in general a small leakage conductance and dielectric losses the effect of which is represented by a small series resistance.

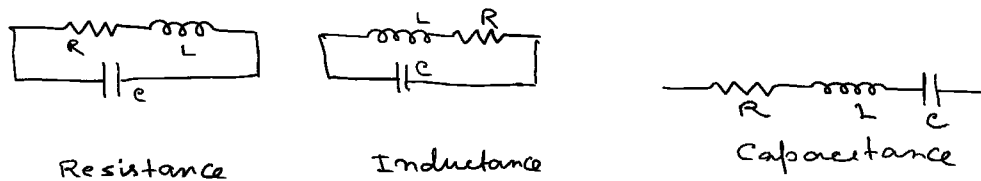


Fig. 2.2.1 : equivalent circuit of resistance, capacitance and inductance Combination:

1. Resistances: this has been discussed in Unit 1.

2. Inductance:

Series combination:

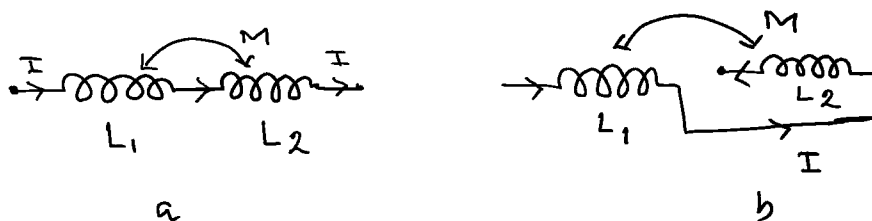


Fig 2.2.2 :

When two inductances L_1 and L_2 are in series as in fig a and b, and a current I is flowing through them, then the induced emf in coil 1 due to self inductance is

$$E_{11} = -L_1 \frac{dI}{dt} \quad 2.2.1$$

Induced emf in coil 2 due to current I in coil 1 is

$$E_{21} = -M \frac{dI}{dt}, \quad 2.2.2$$

where M is the mutual inductance between two coils 1 and 2.

Induced emf in coil 2 due to self inductance is

$$E_{22} = -L_2 \frac{dI}{dt} \quad 2.2.3$$

and the emf-induced in coil 1 due to current I in coil 2 is

$$E_{12} = -M \frac{dI}{dt}, \quad 2.2.4$$

Total emf for fig a is

$$E = E_{11} + E_{22} + E_{21} + E_{12} = -(L_1 + L_2 + 2M) \frac{dI}{dt} \quad 2.2.5$$

Let L_{eq} be the equivalent inductance. Then

$$E = -L_{eq} \frac{dI}{dt} \quad 2.2.6$$

From eqn 2.2.5 and 2.2.6

$$L_{eq} = L_1 + L_2 + 2M \quad 2.2.7$$

For fig 2.2.2b

$$E = E_{11} + E_{22} - E_{21} - E_{12} \quad 2.2.8$$

$$\therefore L_{eq} = L_1 + L_2 - 2M \quad 2.2.7a$$

If $M = 0$ then

$$L_{eq} = L_1 + L_2 \quad 2.2.9$$

Parallel combination

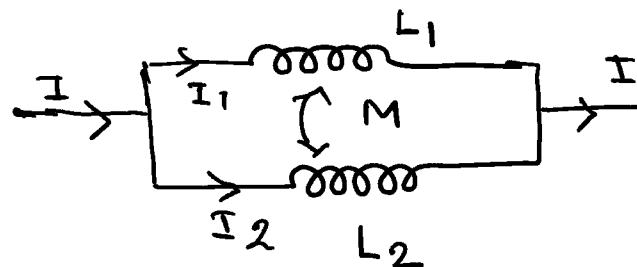


Fig 2.2.3

In the fig. 2.2.3 I_1 current is passing through L_1 and I_2 current is passing through L_2 . Thus induced emf in coil 1 and in coil 2 are respectively

$$E_1 = -L_1 \frac{dI_1}{dt} - M \frac{dI_2}{dt} \quad 2.2.10$$

$$E_2 = -L_2 \frac{dI_2}{dt} - M \frac{dI_1}{dt} \quad 2.2.11$$

Since two coils are in parallel combination,

$$E_1 = E_2 = E$$

$$L_1 \frac{dI_1}{dt} + M \frac{dI_2}{dt} = L_2 \frac{dI_2}{dt} + M \frac{dI_1}{dt} = E \quad 2.2.12$$

By Cramer's rule

$$\frac{dI_1}{dt} = \frac{-E(L_2 - M)}{L_1 L_2 - M^2} \quad \text{and} \quad \frac{dI_2}{dt} = \frac{-E(L_1 - M)}{L_1 L_2 - M^2} \quad 2.2.13$$

Now

$$\frac{dI}{dt} = \frac{dI_1}{dt} + \frac{dI_2}{dt} = \frac{-E(L_1 + L_2 - 2M)}{L_1 L_2 - M^2} \quad 2.2.14$$

$$\therefore E = \frac{(L_1 L_2 - M^2)}{(L_1 + L_2 - 2M)} \frac{dI}{dt} \quad 2.2.15$$

If L_{eq} be the equivalent inductance, then

$$E = -L_{eq} \frac{dI}{dt} \quad 2.2.16$$

Comparing eqn 2.2.15 and 2.2.16

$$L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M} \quad 2.2.17$$

Or, when mutual flux opposes self flux

$$L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + L_2 + 2M} \quad 2.2.17a$$

If $M = 0$,

$$L_{eq} = \frac{L_1 L_2}{L_1 + L_2} \quad 2.2.18$$

3. Capacitance:

Series combination

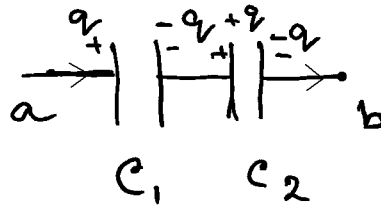


Fig 2.2.4

Let C_1 and C_2 be the two capacitors connected in series. Let the p.d across a and b be V_{ab} . During charging same current flows through capacitors for same time, so that the capacitors acquire the same charge q . Now

$$V_1 = \frac{q}{C_1} \text{ and } V_2 = \frac{q}{C_2}.$$

$$\text{Now, } V_{ab} = V_1 + V_2 = q \left(\frac{1}{c_1} + \frac{1}{c_2} \right) \quad 2.2.19$$

If C be the equivalent capacitance, then

$$V_{ab} = \frac{q}{c} \quad 2.2.20$$

$$\therefore \frac{1}{c} = \left(\frac{1}{c_1} + \frac{1}{c_2} \right) \quad 2.2.21$$

or, for n number of capacitors,

$$\frac{1}{c} = \sum_1^n \frac{1}{c_i} \quad 2.2.21a$$

Parallel Combination:

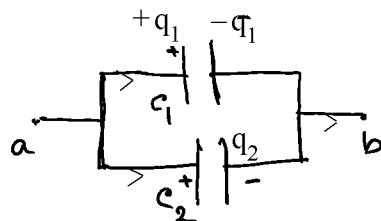


Fig 2.2.5

If V_{ab} be the potential difference across the terminals a and b then the charges on two capacitors will be

$$q_1 = C_1 V_{ab} \text{ and } q_2 = C_2 V_{ab} \quad 2.2.22$$

Now total charge

$$q = q_1 + q_2 = (C_1 + C_2) V_{ab} \quad 2.2.23$$

If C be the equivalent capacitance, then

$$q = C V_{ab} \quad 2.2.24$$

$$\therefore C = C_1 + C_2 \quad 2.2.25$$

or

$$C = \sum_1^n C_i \quad 2.2.25a$$

2.3 Rules to analyse DC sourced electrical circuit

DC circuits may be analysed by some simple rules.

1. Identify a DC circuit.
2. Identify series and parallel elements in a DC circuit.
3. Identify various types of sources; voltage or current sources.
4. For complex circuit, identify different meshes.
5. Now write down the equation involving resistances and dc sources for a particular mesh and then solve the equations.

Simple circuits can be analysed using Ohm's law. But in practice most circuits are not simple and these can be simplified by using Kirchhoff's two laws. These are discussed in chapter 1.

2.4 Current and Voltage drop across the DC circuit elements

They are determined by Ohm's law, Kirchhoff's law, Thevenin's Theorem, Norton's Theorem and superposition theorem. These theorems are important for network analysis. Ohm's law, Kirchhoff's law, and Thevenin's Theorem are discussed in chapter 1. Here we shall discuss Norton's theorem and superposition theorem.

2.4.1 Superposition Theorem

In any linear network containing linear impedances and potential sources the current flowing in any element is the sum of the currents flowing in the element due

to individual potential sources; with the sources being replaced by their internal impedances. Thus considering the following fig,

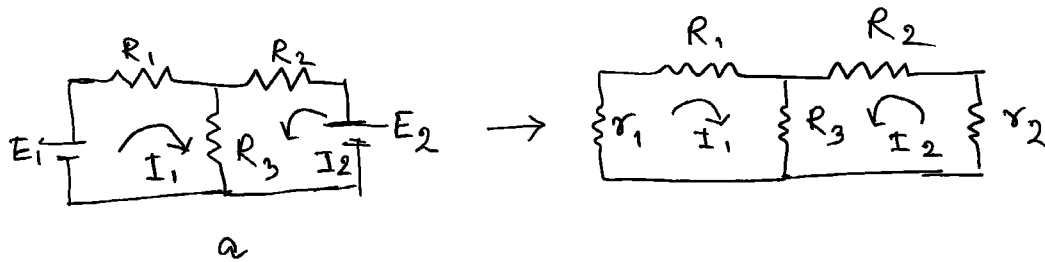


Fig 2.4.1 :

$$E_1 = (R_1 + R_3 + r_1)I_1 + R_3I_2 \tag{2.4.1}$$

$$E_2 = R_3I_1 + (R_2 + R_3 + r_2)I_2 \tag{2.4.2}$$

The currents I_1 and I_2 are obtained by

$$I_1 = \frac{\begin{vmatrix} E_1 & R_3 \\ E_2 & (R_2 + R_3 + r_2) \end{vmatrix}}{\begin{vmatrix} (R_1 + R_3 + r_1) & R_3 \\ R_3 & R_2 + R_3 + r_2 \end{vmatrix}} \text{ and } \tag{2.4.3}$$

$$I_2 = \frac{\begin{vmatrix} E_1 & R_1 + R_3 + r_1 \\ E_2 & R_3 \end{vmatrix}}{\begin{vmatrix} R_1 + R_3 + r_1 & R_3 \\ R_3 & R_2 + R_3 + r_2 \end{vmatrix}} \tag{2.4.4}$$

This theorem is also applicable when resistances are replaced by impedances and DC sources are replaced by AC sources.

2.4.2 Norton's Theorem

Any two terminal network containing resistances and voltage sources may be replaced by a current source in parallel with a resistance. The current (Norton's current) is the short circuit current which is obtained when the two terminals are short circuited and the resistance (Norton) is obtained when viewed across the two terminals with all the emf sources replaced by their internal resistances.

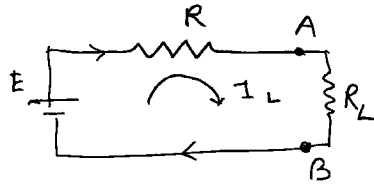


Fig 2.4.2a :

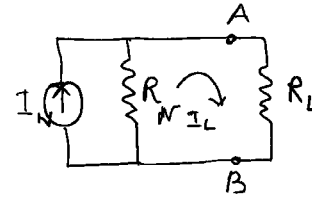


Fig 2.4.2b :

Following the fig 2.4.2a

$$I_L = E/(R + R_L) \quad 2.4.5$$

Also from fig 2.3.2b

$$I'_L = \frac{R I_N}{R_N + R_L} \quad 2.4.6$$

If $R_N = R$, then $I'_L = I_L$

Thus we get $I_N = \frac{E}{R}$.

This is the Short circuit current of Thevenin's equivalent network. This theorem is also applicable when resistances are replaced by impedances and DC sources are replaced by AC sources.

2.4.3 Maximum Power transfer Theorem

It states that the power received in a network from another connected network will be maximum when the resistance(impedance) of the receiving network will be equal to the resistance (impedance) of the connected network looking at its two terminals.

2.5 Single phase and three phase alternating current Sources

2.5.1 Single phase

Alternating voltage may be generated by

i) Rotating a coil in a magnetic field ii) By rotating a magnetic field within a stationary coil.

When the coil (armature) rotates within the poles of an external field or the field is rotating keeping the coil stationary, the magnetic flux linked with the coil changes

and thus an emf is induced. If N be the number of turns and A the area of the coil then the magnetic flux ϕ linked with the coil is given by

$\phi = NAB \cos \theta$, where θ is the angle made by the normal of the coil with the direction of magnetic field B . If the angular velocity of rotation of the coil is ω then the induced emf e is given by

$$e = -\frac{d\Phi}{dt} = -\frac{d}{dt} (NAB \cos \omega t) = E_0 \sin \omega t$$

Where $E_0 = NAB \omega$, when $\theta = 0$ (i.e B is in horizontal direction and the coil is in vertical position). When the coil is in horizontal position then $\theta = \pi/2$; e is maximum. It is again zero when $\theta = \pi$ and maximum in the negative direction when $\theta = 3\pi/2$. Again it is zero when $\theta = 2\pi$. This is represented in the fig. below.

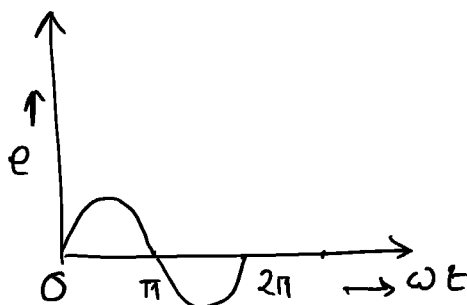


Fig 2.5.1 :

This type of AC supply is called single phase AC supply.

The value of voltage will depend upon the no. of turns of the coil, field strength and speed of rotation.

2.5.2 Three phase alternating current Sources

In three phase alternating current source three coils are arranged at 120° apart from each other on the same axis and are rotated with constant speed in a uniform magnetic field. Then the emf induced in them will have a phase difference of 120° with respect to one another. The emf.s are given by

$$E_1 = E_0 \sin \omega t, E_2 = E_0 \sin \left(\omega t + \frac{2\pi}{3} \right), E_3 = E_0 \sin \left(\omega t + \frac{4\pi}{3} \right).$$

The starting point of the three windings is made common and is called the neutral. In this way power can be handled by three heavy transmission wires and one light one. There are two ways of connecting these wires.

1. Star connection:

There is a common point of the three wires which is called star point. The total current at the star point is zero. The wire connected at this point is known as neutral wire and the three wires connected at the other end of three wires are known as phase wires. Load can be connected between any of the three phase wires and the neutral. Let V_0 be the amplitude of the voltage applied to any phase wire, then the voltage difference between two phase wires, is given by

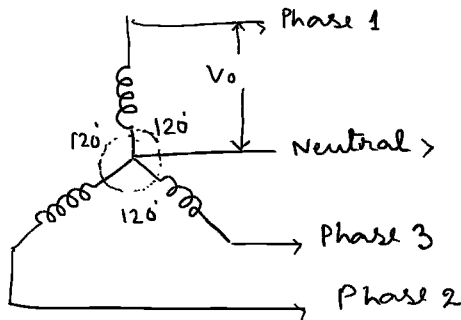


Fig 2.5.2a :

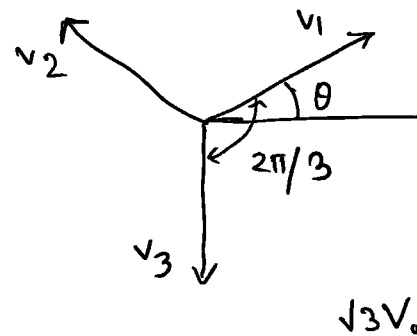


Fig 2.5.2b :

$$V = V_2 - V_1 = V_3 - V_2 = V_3 - V_1 = \sqrt{3}V_0 \cos\left(\omega t + \frac{\pi}{3}\right).$$

The amplitude is $\sqrt{3}V_0$ and the phase angle is $\frac{\pi}{3}$. In this connection line current is same as phase current.

2. Delta connection:

Here three windings are joined in series. Hence the line voltage (difference of voltage between two phase wires is same as that across each winding which is known as phase voltage. If I_0 is the amplitude of current, then line current is

$$I = I_2 + I_1 = \sqrt{3}I_0 \cos\left(\omega t + \frac{\pi}{3}\right).$$

Which is equal to $\sqrt{3}$ times the phase current.

The power consumption in both the cases is same.

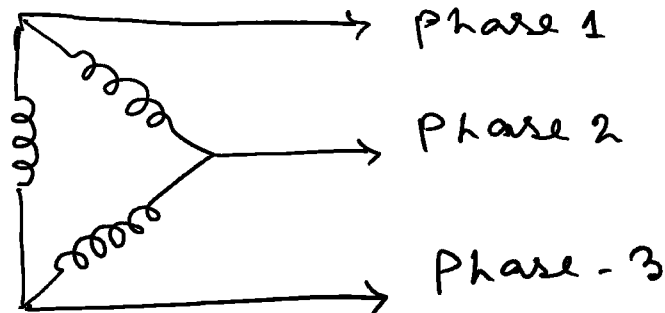


Fig 2.5.3 :

2.6 Rules to analyse AC sourced electrical circuits

AC circuits may be analysed by some simple rules.

1. Identify a AC circuit.
2. Identify series and parallel elements in an AC circuit.
3. Identify various types of AC sources; voltage or current sources.
4. For complex circuit and network, identify different meshes.
5. Now write down the equation involving resistances, inductances, capacitors and ac sources for a particular mesh and then solve the equations.

For the analysis of ac sourced electrical circuits, Kirchhoff's laws which were discussed earlier for dc circuits can also be applied. Here they are defined in complex terms.

Current law:

As there is no accumulation of electric charges in a system of conductors, the sum of complex currents entering any junction is equal to the sum of complex currents leaving the junction.

Voltage law:

The sum of the complex emfs in any mesh is equal to the sum of the complex potential drops across all the circuit elements in that mesh.

Thevenin's theorem, Norton's theorem can also be applied by replacing resistances by impedances.

2.7 Real Imaginary and Complex power

In a passive network in ac circuit, there is power dissipation in resistor and power stored in inductor or capacitor. The power dissipated in the resistor is called active or **real power** and the power stored in the reactive component is called reactive or **imaginary power**, so that the total power is complex and it is given by

Complex power = real power +j imaginary power.

2.8 Components of AC Source

Power Factor:

In an ac circuit, if v and i are instantaneous voltage and current in the circuit, then the mean rate of doing work or average power is given by

$$P = \frac{1}{T} \int_0^T vi dt,$$

where $v = V_0 \sin \omega t$ and $i = I_0 \sin (\omega t - \phi)$, ϕ , is the phase difference between voltage and current.

Putting the value of v and i we get

$$P = \frac{V_0}{\sqrt{2}} \cdot \frac{I_0}{\sqrt{2}} \cos \phi = V_{rms} I_{rms} \cos \phi$$

For DC circuit the rate of doing work or power is given by VI . But in AC, $V_{rms} I_{rms}$ does not give the true power. It is the apparent power. Thus

True power = Apparent power $\times \cos \phi$

Here $\cos \phi$ is called the power factor of the circuit. Thus to get the actual power, the apparent power must be multiplied by the power factor. When ϕ is zero, voltage and currents are in phase and true power is equal to apparent power. This is the case for resistive circuit. When ϕ is 90, power factor is zero and the work done is zero. In this case the current is called wattless current. This is true when the circuit is purely inductive or capacitive. This can be explained from the graph below. Here v and i are drawn in the same curve. The power is plotted along the ordinate corresponding to the product vi for all time. When the voltage and current are in the same direction

CB, supply is doing work on the circuit. But when the voltage and current are in the opposite direction (AC), circuit is doing work on the supply. When ϕ is 90° , positive area and negative area of the curve cancels each other and the power is zero.

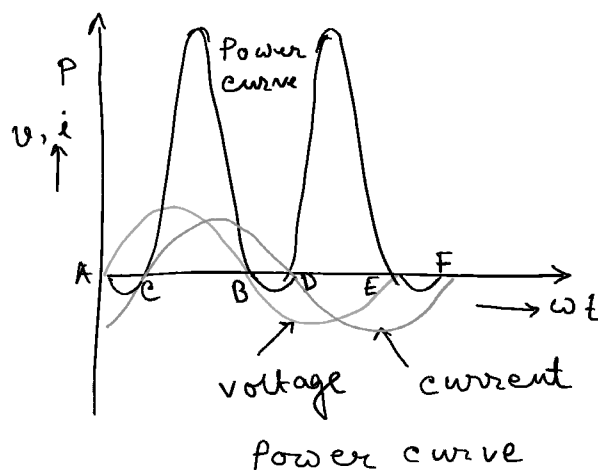


Fig 2.8.1 :

2.9 Saving energy and Money

It is known that energy costs money, So if we can save energy (electrical) we can save money

1. **Use of Thermostat:** Department of Energy (DOE) recommends setting the air conditioner to 78°F and the furnace to 68°F to keep the house comfortable while reducing energy costs and decreasing the demand on the energy grid. A programmable thermostat lets us make the house hotter or cooler during periods when we aren't at home. For nonprogrammable thermostat we have to adjust it manually.
2. **Use of energy star appliances:** Energy Star also identifies energy-efficient appliances, including washers, dryers, refrigerators, freezers, dishwashers, room air conditioners, and more. When shopping for new appliances, we should look for the Energy Star label, without much compromising with our money.
3. **Un plugging the appliances:** Stereos, DVD players, televisions, kitchen appliances, and any other plugged-in appliances draw a small amount of

power even when turned off. Use of surge suppressor to turn them completely off when not in use, or unplugging these items until we really need them is recommended

4. **Use of Energy efficient bulb:** A quick and easy way to reduce our energy is to replace existing incandescent bulbs with energy-efficient compact fluorescent ones.
5. **Maintenance:** Cleaning of the filter on our air conditioner regularly is recommended.

2.10 Summary

When circuit becomes complicated then making it simpler by using series and parallel combination theory is not applicable. For complicated circuit we use Norton theorem. Star and delta network theorem. For ac circuit there is a concept of phase and network theorem is applicable to solve the complicated circuit.

2.11 Short questions

1. What are main electrical circuit elements? Describe briefly.
2. Define resistor, inductor and capacitor.
3. Derive equivalent inductance of two inductors joined in a) series, b) in parallel.
4. Derive equivalent capacitance of two capacitors joined in a) series, b) parallel.
5. How single phase alternating current source can be produced?
6. What are the two types of connections in three phase alternating current source? Describe the connections.
7. What is power factor? State the relation between true power and apparent power? When current can be called as wattles current.
8. Describe briefly how energy can be saved in electrical equipments and appliances.

9. State maximum power transfer theorem.

10. Using principle of superposition calculate potential drop across 5 k ohm resistor in the following circuit. Ans 24V.

Ans. a) Replace the current source by its infinite internal resistance and get the potential difference across 5kΩ due to 18V only.

$$\text{Then } v_1 = \frac{18 \times 5}{2 + 3 + 5} \text{ qv} = \text{qv}$$

b) Now to find the effect of 6 mA source, we get the p.d across 5 kΩ as $v_2 = 5 \times 3 = 15\text{V}$, current through 5 kΩ being 3 mA.

∴ From superposition Theorem total pd across 5 kΩ resistor is $(9 + 15)\text{V} = 24\text{V}$.

Unit 3 □ Electrical Drawing and Symbols

Structure

- 3.0 Objective
- 3.1 Introduction
- 3.2 Electrical Drawing and Symbols
- 3.3 Blue Prints
- 3.4 Electrical Schematics and Reading Schematics
- 3.5 Ladder diagram
 - 3.5.1 Ladder diagram meaning
 - 3.5.2 Reading of Ladder diagram
 - 3.5.3 Importance of wire no
 - 3.5.4 Ladder logic circuit
- 3.6 Power circuit and control circuit
- 3.7 Summary
- 3.8 Short questions

3.0 Objective

In this chapter you gather knowledge on the following topics

- Standard Electrical symbol
- Electrical schematics
- Name of components
- Ladder Diagram
- Power circuit and control circuit

3.1 Introduction

For troubleshooting an electrical circuit, a schematic diagram is very important. In schematic diagram, electrical components are represented by some well defined symbols. It is also important to know the concept of ladder diagram which easily represent the connections of circuit elements in circuit operation.

























3.2 Electrical Drawing and Symbols

Drawing Symbols:

Electrical Symbols:

Electrical symbols represent electrical components which are used for drawing schematic diagram. Following is the table of some important electrical symbol (within the scope of this syllabus).

Reference	Component name	Symbol	Meaning
Wire	Electrical wire Connected wire Not connected wire		conductor
Switch	SPST toggle switch SPDT toggle switch Push button switch (NO) Push button switch (NC)		Disconnects current in open position Selects between two connections alternately Momentary switch Normally open (NO) Normally closed (NC)
Relay	SPST SPDT		Relay open/close connection by an electromagnet
Ground Symbols	Earth ground Chassis ground Common ground		Zero potential reference and electrical Shock protection Connected to chassis of the circuit Common ground
Resistor	Resistor (IEEE) Resistor (IEC) Potentiometer (IEEE) Potentiometer (IEC)		Used to adjust current flow Adjustable resistor (3 terminals)
	Rheostat (IEEE) Rheostat (IEC)		Adjustable resistor two terminals
	Thermistor Photo resistor		Change resistance with temperature Change resistance with light intensity

Reference	Component name	Symbol	Meaning
Inductor	Variable Iron cored	 	Stores magnetic field
Capacitor	Normal Polarised Variable	   	Stores electrical energy Short circuit with AC and open circuit with DC Electrolytic Adjustable
Meter	Voltmeter Ammeter Ohmmeter Wattmeter	   	Measures voltage Measures current Measures resistance Measures electric power
Power supply	Battery Generator	     	Voltage source constant voltage cell battery Generates alternating voltage Generates voltage Current source
Solder bridge			Solder close connection
Diode	Normal diode Zener diode Light emitting diode Photo diode	   	Allows current flow in one direction Allows current flow in reverse direction in breakdown condition Emits light when current flows Current flows when exposed to light.
Lamp	Light bulb	  	Generates light when current passes through it

3.3 Blue Prints

Blue Prints play an important role in designing the electrical plan in buildings. It is a two dimensional drawing for a project. It helps to show how wires, light fixtures, receptors and other parts of an electrical system should be installed. Electricians can easily figure out them and decode crucial information from them.

Blue prints may be in the form of schematics or diagram.

Electrical drawings for a project include,

- Site Plan: It shows overall location of the building as well as external wiring.
- Floor Plan: It shows the layout of electrical systems in every level of the building.
- Wiring Diagram: It shows the various physical connections and the electrical circuits to be installed.
- Schedule: It shows the longevity of electrical installation. It may include information of payment intervals, working hours of contractors.

To understand electrical blue print property, step by step instructions may be followed.

- Study architectural floor plan
- Analyse the symbols legend
- Review the wiring diagrams
- Access lighting plans
- Understand the specification manual

Understanding of electrical blue print is important because it saves time, money and improves safety.

3.4 Electrical Schematics and Reading Schematics

Electrical schematics:

An electrical circuit is composed of required electrical components connected by wires. The electrical schematic is a diagram which shows how the components are

connected in the circuit and it helps to understand how a circuit works. It is very useful for troubleshooting circuits.

Reading Schematics:

Once we know the most common schematic symbols of the components (i.e resistors, capacitors, transistors etc), the reading of electrical schematics is easy and useful. It also helps us to modify a circuit if one wants. In a circuit diagram, one should understand which components relate to which symbol and how these symbols are connected together.

Each physical component has a unique schematic symbol.

A. Power source:

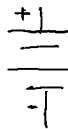
- a) DC power source: It provides electrical current in a definite direction.



- b) AC power source: It provides current which can change directions.



- B. Battery: It is a type of DC power source. Positive terminal is represented by longer line while the shorter line represents negative terminal.



- C. Ground: It often refers to negative side of a circuit.



- D. Terminals: They are the connection points to external circuit. For external connection it is represented as blank circle while for nodes or junctions it is represented as solid circles.

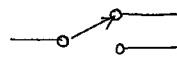


E. Switches. It can change the path of current flow. It is used to make or break a connection in a circuit.

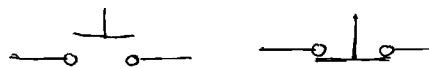
SPST (Single Pole Single Throw) Switches: It is an on or off switch.



SPDT (Single Pole Double Throw) It can direct the path of current to different parts of a circuit.

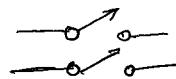


Momentary Switches: It remains momentarily open or closed while being pressed (Push button switches)



Multi point Switches :

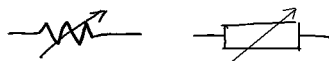
DPST and DPDT are these classes of switches.



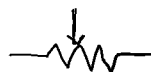
F. Resistors: It restricts current flow by its resistive property.



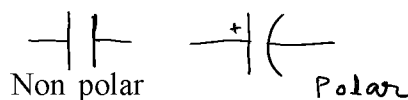
Variable resistors: It's resistance can be increased or decreased.



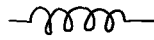
G. Rheostat: It is a three terminal variable resistor.



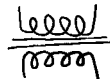
H. Capacitors: It is a passive electrical component which store electrical charge



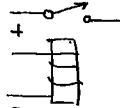
- I. Inductors: It is a passive component which create a magnetic field when current flows through it.



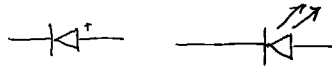
- J. Transformers: It is used to step up or step down voltages.



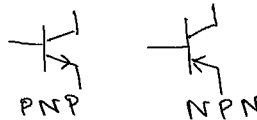
- K. Relays: It is an electrically operated switch.



- L. Diodes: It can be used as a rectifier.



- M. Transistors: Used as oscillators or amplifiers:



- N. Fuses: Fuses provide over current protection in an electrical circuit.



- O. Motors: Motors converts electrical energy into mechanical energy.



Now defining all the symbols, in an electrical circuit it is necessary to identify how all the symbols are connected together

Wires and connectors:

Nets, Nodes

Schematic nets tell us how components are wired together in a circuit. Nets are represented as lines between component terminals. Sometimes (but not always)

they're of a unique colour: When there are too many nets to be shown, the nets are given a name and are labelled.

Representation of wires and connections in a schematic are represented below. Wires are represented by lines and connections are represented by dots. Schematic symbols when wires are physically connected in a circuit are given below. The dots are called nodes. When there is no node, it means the wires are not connected.

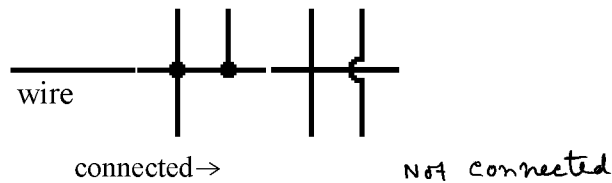


Fig 3.4.1

The schematic diagram of a simple circuit consisting of a resistance, a LED, a battery and a switch is shown below.

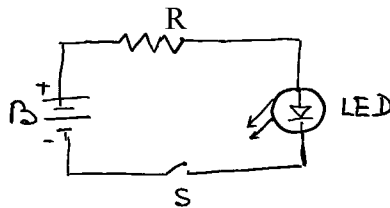


Fig 3.4.2

Reading schematics is very much important in schematic diagram. It is important to recognise the components. For completion, each symbol may be designated by names and values.

Values and Names

To know exactly what a component is, say for the case of resistors, capacitors, and inductors, values will tell us how many ohms, farads or henries they have. The value will specify the important characteristics of a schematic component. In case of crystals, the frequency may be listed as its important value.



Fig 3.4.3

To identify the type of component, usually a combination of one or two letters and a number is used. Each component name on a schematic must be unique; Component names help us reference specific points in schematics.

Here is a table of common components and their name prefixes:

Component names

Name Identifier	Component
R	Resistors
C	Capacitors
L	Inductors
S	Switches
D	Diodes
Q	Transistors
U/IC	Integrated Circuits
Y/XTAL	Crystals and Oscillators

The above diagram with values is shown below.

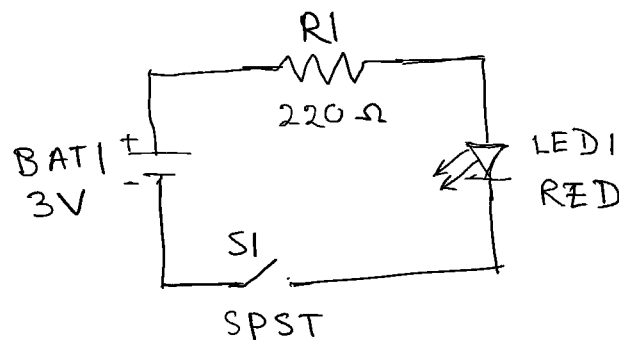


Fig 3.4.4

3.5 Ladder diagram

3.5.1 Ladder diagram Meaning :

Ladder diagram provides fast and easy understanding of the connection of electrical components in a circuit operation. Ladder diagram can be divided into two distinct portions; power portion and control portion. The primary focus of the power

portion is to show the flow of power to motor or other devices. The control portion shows the control of the motor. Fuses and disconnect devices may appear in both power and control circuits. The use of symbol is important in both power and control. Graphic symbols, abbreviations and device designations are drawn as per industry standards. In contrast to one line diagram, ladder diagrams often show multiple lines leading to and from components whether they are in series or in parallel connections.

- Such diagrams resemble a 'ladder', and hence they are called 'ladder' diagrams. It has two vertical 'rails' (supply power) and one or more 'rungs' (horizontal lines) to represent the control circuits. Thus these are the two basic parts in ladder diagram; the **rails and the rungs**.

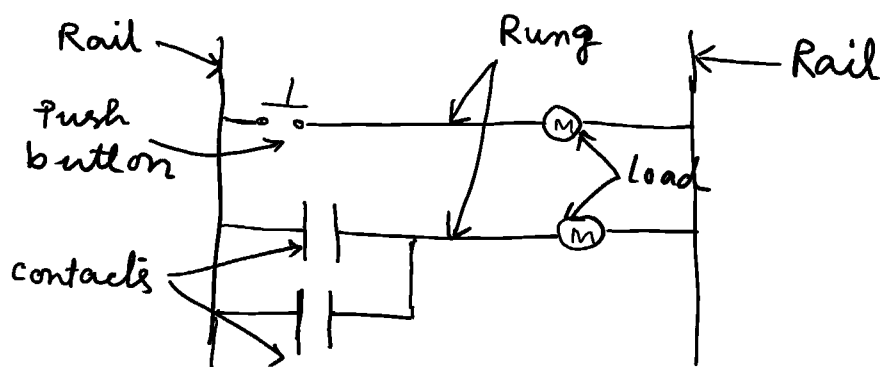


Fig 3.5.1

- The 'rails' are the two vertical lines that represent the power source to the control circuit. Depending on the rated values of the loads connected in the circuit, the control circuit voltage is usually rated as 12V-120 V.
- The 'rungs' are the horizontal lines which illustrate the interconnections between control devices and loads to make up the control circuit.

3.5.2 Reading of Ladder Diagram :

1. In order to understand the sequence of the operation, the ladder diagram is read from left to right and then from up to down.
2. The loads in the ladder diagram are always connected in parallel on the rungs.

3. The load is almost always connected at the right hand side of the rung. The control devices are connected between the left side of the rail and the load. This is important for reliable operation.*

Consider the following ckt.

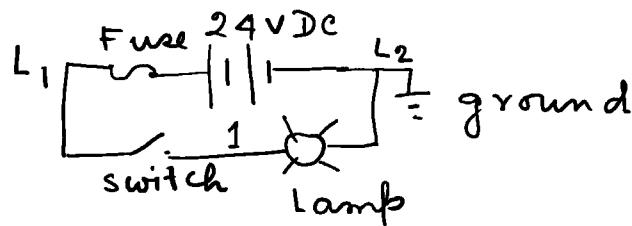
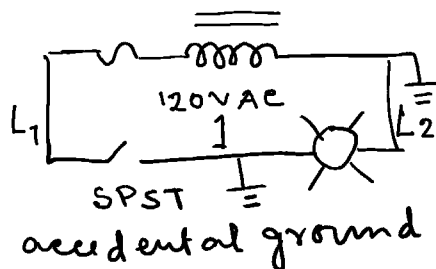
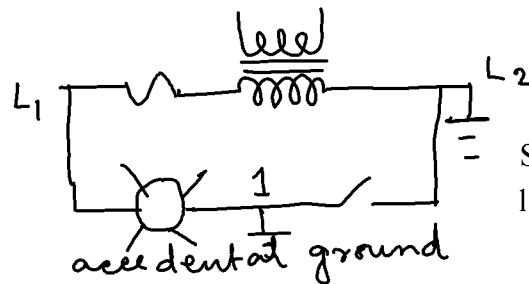


Fig 3.5.2



Fuse will blow off if the switch is closed and the lamp cannot light up.

Fig 3.5a



Switch has no effect and the lamp is energised.

Fig 3.5b

Here the ground connection for the power source is connected to the right end of the rail. The lamp is located on the right side of the rung (fig3.5). This is a good practice. If the wire #1 is accidentally come in contact with ground (fig 3.5a), the lamp will be shorted out and will not receive power. If the switch is now closed, there will be a short circuit and the fuse will blow off. However, with the same fault (fig 3.5b), the switch will have no effect when the position of switch and lamp is

interchanged, and the accidental grounding will energise the lamp uncontrollably. This is not good practice. It is safer to have a system that blows off a fuse in the event of ground fault.

3.5.3 Importance of wire no :

- In ladder diagram, each conductor has its own unique wire number and/or letters for the control system in which it is used. In fig 3 number 1 is assigned to the wire between switch and lamp. Wires leading to the switch would be labelled L_1 and 1 respectively. Wires leading to the lamp would be labelled 1 and L_2 respectively. Wire numbers do not change at any junction or node.
- Ladder diagram picture:



Fig 3.7 : A simple ladder diagram showing a lamp that is controlled by a switch

Each node of a circuit is to be assigned a unique number. Any electrically continuous point in a control ckt, possess the same wire no. The example 2 below displays the use of a single node with several branches; the wire 2 is a single electrically continuous point connecting to many different devices.

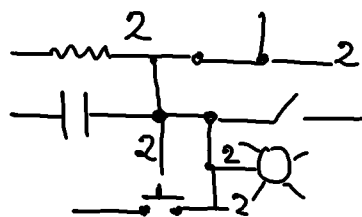


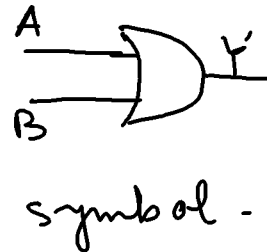
Fig 3.5.3.1

3.5.4 Ladder logic circuit

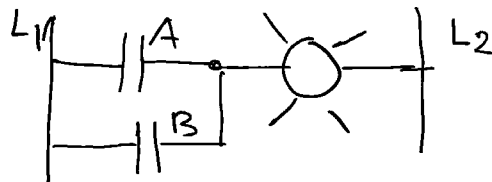
For a programmable logic circuit (PLC), the ladder diagram is useful.

- Let us construct the ladder diagram of OR logic gate. The truth table for OR logic is

A	B	$Y=A+B$
0	0	0
0	1	1
1	0	1
1	1	1



Consider the hypothetical lamp circuit (fig 1). We can construct the ladder diagram of OR logic with additional rung with our original ladder.



The lamp will glow (or energised) if either of the contacts A or B is activated and current from L_1 to L_2 goes to the lamp.

3.6 Power circuit and control circuit

Power circuit:

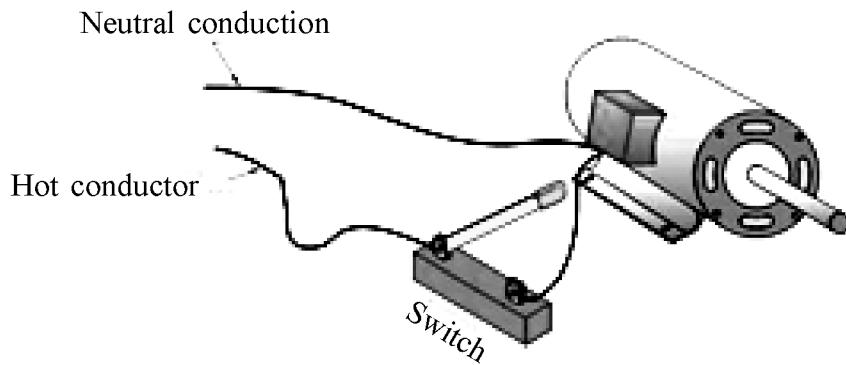
A circuit which is used to operate a load by carrying electricity is called a power circuit. A simple example is a circuit with a source and a motor as a load connected properly may serve as power circuit. Most power circuits provide power to devices to operate it. **Power circuit is used to control the power flow to the load and the control circuit is used to control the power circuit**

Control circuit:

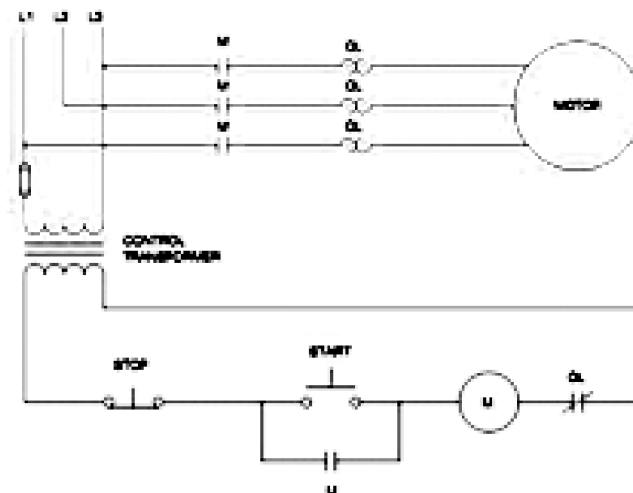
A control circuit is a special type of circuit which is used to control a separate power circuit. For the power circuit as mentioned above there must be a switch in series with the motor. The switch is the circuit control. The control circuit is used so that the motor is started and stopped in a safe manner for the safety of the device. The common example of a control circuit is the thermostat which is a low voltage control circuit used in the air conditioner in a house. It controls a relay which energises and de-energises the power circuit to the air conditioning compressor.

Control circuit may be divided into two major types.

- i) Two wired control circuit which may be a single switch to make and break connection to a motor which is just a single phase manual starter



- ii) Three wire control circuit. It uses momentary contact devices such as push buttons. Three wires run from the push button control to the starter. Because of its flexibility, it is used extensively in industry. Pilot control devices can be mounted in remote locations. The advantage of three wire control circuit is that in case of a power failure, when power is restored, the system won't restart automatically and this gives a safety issue of the motor.



The difference between power circuit and control circuit:

Power circuit is used to control the power flow to the load and the control circuit is used to control the power circuit.

3.7 Summary

It is essential to represent the electrical object like resistance, capacitor, battery etc by symbol in order to draw and solve any numerical problem which are well defined and universally used by the Physics Community. Ladder diagram is one of a kind to understand the circuit operation.

3.8 Short questions

1. What is meant by electrical symbols: Draw electrical symbols of resistors, capacitors, inductors, transformers, AC and DC power supply.
2. What is the role of Blue print in designing electrical design of a building?
3. How do you read electrical schematics in a circuit? What is nets and nodes in electrical schematics?
4. What is ladder diagram? What are the two basic parts of ladder diagram?
5. How ladder diagram is read in a circuit? What is the importance of wire number in ladder logic?
6. What is meant by power circuit and control circuit?
7. Exercise: Construct ladder diagram for AND or NOT logic.
8. Construct ladder diagram for AND or NOT logic.

Ans

The truth tables are given by

AND

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

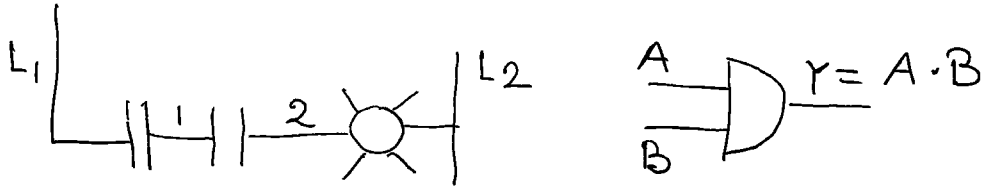


Fig and symbol

The lamp will be energised only when contact A and contact B are simultaneously closed or activated.

NOT

A	Y
0	1
1	0

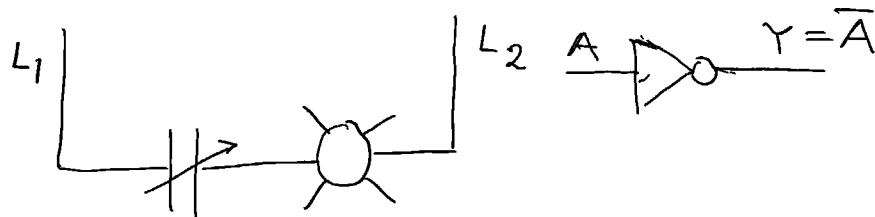
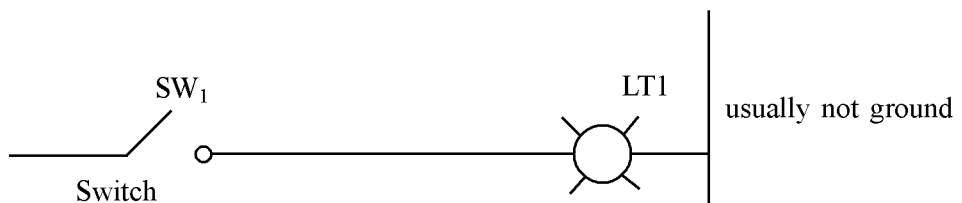


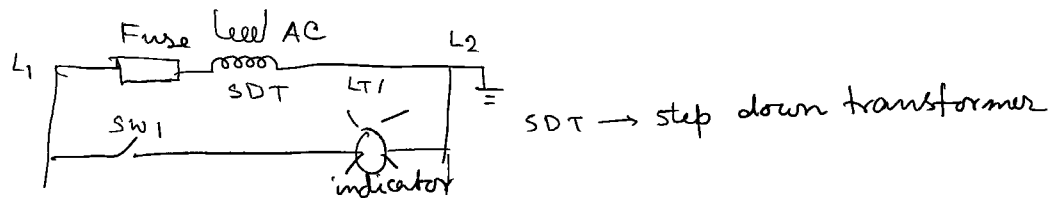
Fig and symbol

The lamp will be energised if contact A is not activated and will be deenergised when contact A is activated.

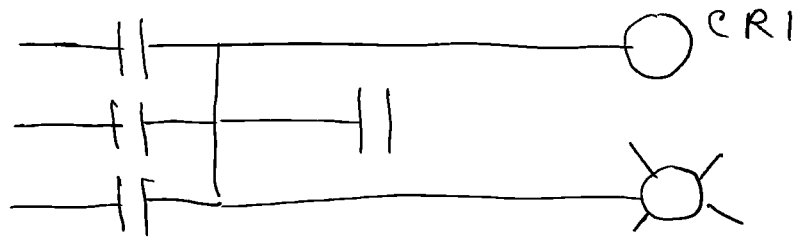
9. a) Wire the following circuit and describe what happens when the switch closes.



b) Also show the diagram when the DC is replaced by AC BUS.



10. Give the line number for the ladder diagram shown below which displays the use of single node with several branches.



Unit 4 □ Generators and Transformers

Structure

- 4.0 Objectives
- 4.1 Introduction
- 4.2 DC Power source
- 4.3 Inductance, Capacitance and Impedance
- 4.4 Operation of transformers
- 4.5 Summary
- 4.6 Short questions

4.0 Objective

In this chapter you gather knowledge on the following topics

- DC Power source
- AC/DC generators
- Transformer and its application

4.1 Introduction

We are familiar with the term Generators and Transformers. A generator converts mechanical energy into electrical one. They are both AC and DC generators. Transformers are electrical devices used to step up or step down electrical energy by means of magnetically coupled circuits.

4.2 DC Power source

Standard batteries, power supply are examples of common dc power sources. The standard batteries convert chemical energy into electrical energy. A dc power supply is an electrical device which supplies a constant dc voltage to its load. It converts electric current from a source to correct voltage; current and frequency. Generators are devices which converts mechanical energy into electrical energy (power) for the use in an external circuit. They are also the source of dc power. It works on the principle of Faradays law of electromagnetic induction.

AC/DC Generator:

An electrical generator is a machine which converts mechanical energy into electrical one. Mainly generators are of two types: an AC generator and a DC

generator. AC generator also known as alternator creates an alternating current which reverses direction periodically. But DC generator produces direct current which flows in one direction.

Principle:

According to Faraday's law of electromagnetic induction, when a conductor moves in a uniform magnetic field, the change in magnetic flux cut by the conductor will induce an emf in it. This induced emf will produce an induced current.

Basic parts of a generator:

- (a) A conductor which can move to cut the magnetic flux,
- (b) Arrangement for production of magnetic field.

Construction and working principle:

Let ABCD be a rectangular copper coil called armature rotating about its own axis with an angular velocity ω in a magnetic field produced by strong magnet (either by permanent magnet or electromagnet) called field magnet. In course of rotation of the coil in the magnetic field, the flux linkage will change. An emf is induced in the coil and is given by $e = N d\phi/dt$, where N is the number of turns of the coil and ϕ is the flux linkage with the coil. When two ends of the rotating coil are joined to two slip rings a and b insulated from each other and from the central shaft, the emf is enabled to produce an alternating current in the external circuit. The current produced in the coil is conveyed to the external load resistance R with the help of two carbon brushes pressed against the slip ring.

To produce current in one direction, a device called commutator is used. It consists of a split ring MN, to each half of it is connected one end of a rotating coil. Two brush conductors P and Q bear upon the split ring at opposite ends of a diameter. When the direction of the induced emf changes sign, each segment of the split ring moves on to other brush and hence the emf always acts in one direction in the

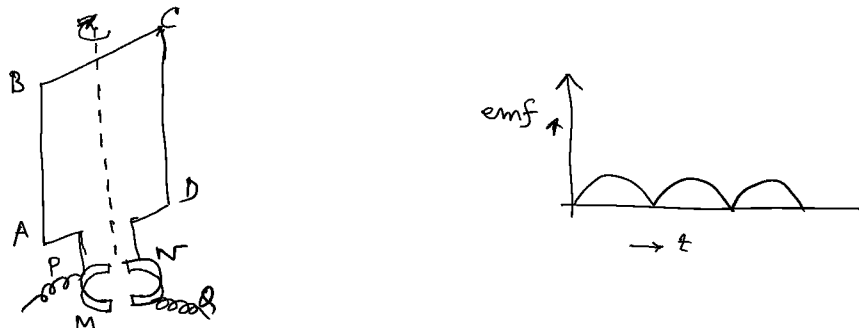


Fig 4.1

external circuit. The emf and current in the external circuit are constant in direction but not in magnitude. We get pulsating direct current.

Such an emf may be written as

$$e = \frac{2e_0}{\pi} - \frac{4e_0}{\pi} \left[\frac{1}{3} \cos 2\omega t + \frac{1}{15} \cos 4\omega t + \dots \right] \quad 4.1$$

It has the DC component $\frac{2e_0}{\pi}$, where e_0 is peak emf but it is accompanied by a series of ripple voltages with fundamentals as two times the rotation frequency.

Continuous or Direct Current:

The presence of ripple is very undesirable in dc generator. Consider a pair of coils whose planes are at right angles to each other. The ends E and H are joined to the commutator section 1 and F and G are joined to section 2. In course of rotation it will be seen that when one coil produces zero emf, the other produces maximum emf. The resultant output though not constant in value but varies between the limits OA and OB (fig 4.2). By increasing the number of coils the emf may be made much smoother.

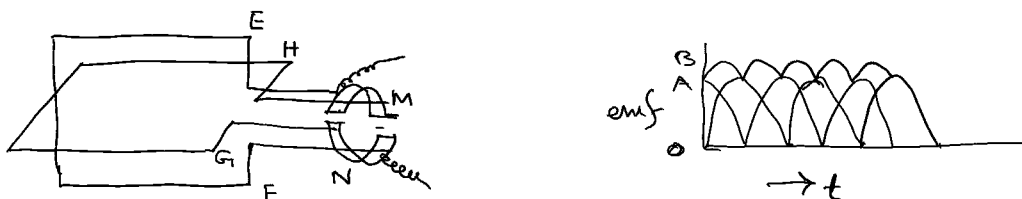


Fig 4.2

Thereby increasing the number of coils the emf and current curves may be made much smoother. Now consider the generator with four coils with eight conductors lying in the slots a, b, c, d, e, f, g, h in an iron core. The conductors are connected to the commutator bars ABCD at the front of the armature (shown by continuous line) and to each other at the back of the armature (dotted lines).

A generator consists of following parts:

Armature:

The armature consists of the core and the winding. To reduce the hysteresis loss, silicon steel material is used for the construction of the core. To minimise eddy

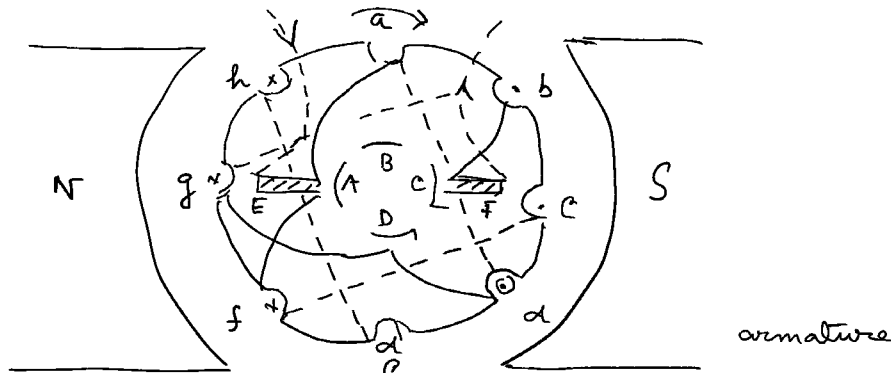
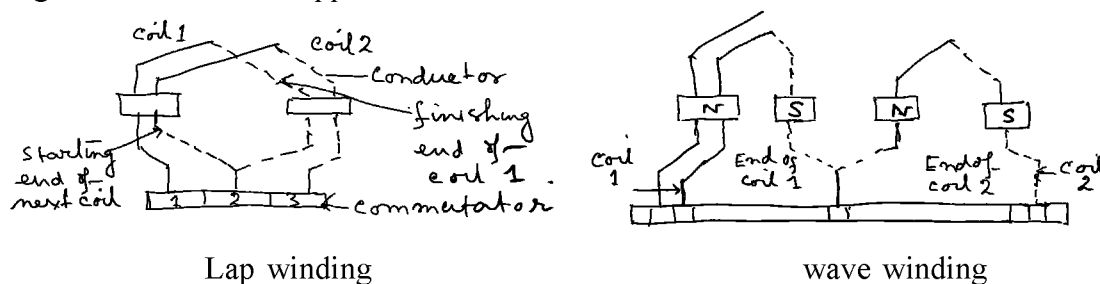


Fig 4.3

current in the core, the core is built of thin iron sheets or discs of about 0.3 to 0.5 mm thickness and insulated from one another by varnish.

There are mainly two types of armature windings: i) Lap winding and ii) Wave winding. In **Lap winding**, the conductors are connected in such a way that the number of parallel paths is equal to the no of poles. In this winding the number of brushes is equal to the number of parallel paths and these brushes are equally divided into negative and positive polarity. The lap winding is mainly used in low voltage, high current machine applications



Lap winding

wave winding

Fig 4.4

In **wave winding**, the conductors are so connected that they are divided into two parallel paths irrespective of the number of poles of the machine. The number of brushes is equal to the number of parallel paths. The wave winding is mainly used in high voltage, low current machines.

Commutator:

The commutator is a cylindrical structure built up of segments of high conductivity copper, insulated from one another by mica. Commutator helps to collect current from armature.

Brushes:

There are two main types of brushes used in generator. (a) The metal brush consists of thin sheet, wire or gauge of brass or copper, (b) the carbon brush is made of compressed graphite. It is normally mounted on the commutator, and with the help of two or more carbon brushes, current is collected from the armature winding. The carbon brush reduces the sparking caused by the back emf induced by the self inductance of the coil.

Types of Generator:

a) **Separately excited:** In this case the field magnets are energised from an independent external source or direct current.

b) **Self excited:** In this case the field magnets are energised by the current produced by the generators themselves. This type of generators may be classified into three types namely series wound, shunt wound and compound wound.

Series Wound: Here the armature A and field coils are in series with external circuit. It can be used for incandescent lamps.

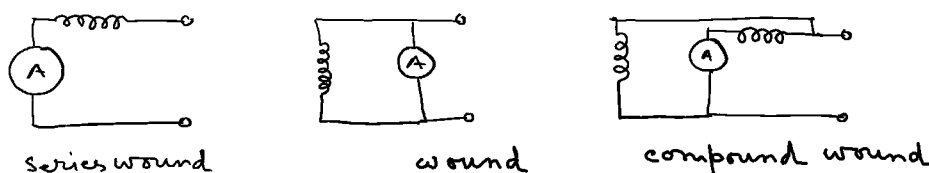


Fig 4.5

Shunt wound: Here the field winding is such that the armature circuit and the field coils are in parallel. It is used for charging accumulators.

Compound wound: This is a combination of series and shunt wound motors. It gives a constant emf for all external currents

Efficiency of a generator:

There are different types of losses in a generator;

- (i) **Copper loss** (armature copper loss, field copper loss and loss due to brush contact resistance),
- (ii) **Iron loss** (hysteresis loss, eddy current loss) and
- (iii) **Mechanical loss** (friction at bearings and commutator, winding of rotating armature). Iron loss and mechanical loss are called stray losses;

The efficiency of a generator is defined as

$$h = \frac{\text{output}}{\text{output} + \text{losses}}.$$

4.3 Inductance, Capacitance and Impedance

Inductance:

Self Inductance:

When the current linked with a circuit changes, the flux linked with the same circuit also changes and an induced emf proportional to the rate of change of total flux in the circuit is developed. This phenomenon is known as self induction.

Coefficient of self induction:

Let flux ϕ passes through each turn of a coil of N turns, then the total flux $N\phi$ will be proportional to the current i flowing through the circuit. i.e

$$N\phi \propto i$$

$$\text{Or,} \quad N\phi = Li \quad 4.2.1$$

Here L is known as the coefficient of self inductance of the coil. From Faraday's Law of electromagnetic induction, the induced emf

$$E = -\frac{d}{dt}(N\phi) = -L\frac{di}{dt} \quad 4.2.2$$

Thus self inductance may be defined from eqn 4.2.1 and eqn 4.2.2 as i) the flux linked with the circuit when unit current flows in it, ii) the induced emf produced in the circuit when the rate of change of current in it is unity. L depends on size, shape and number of turns of the coil.

Self inductance for a long solenoid: For a long solenoid of length l , total number of turns N , and of area of cross section A , for a current i passing through the solenoid, the magnetic flux linked with the coil is



Fig 4.5

$$\phi = \mu_0 \left(\frac{N}{l} \right) iA \quad 4.3.3$$

Therefore, induced emf is

$$E = -\frac{d}{dt}(N\phi) = -\frac{\mu_0 N^2 A}{l} \frac{di}{dt} \quad 4.3.4$$

Comparing with equation 4.2.2, the self inductance of the coil is given by

$$L = \frac{\mu_0 N^2 A}{l} \quad 4.3.5$$

Mutual inductance:

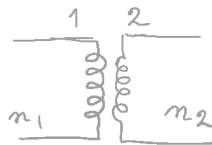


Fig 4.6

The change in the current in one coil can produce an induced emf in a neighbouring coil. If N_1 and N_2 be the number of turns in primary and secondary respectively, a current in coil 1 sets up a magnetic flux and some of the lines of force will pass through the second coil 2. Then the total flux associated with N_2 turns of secondary is

$$N_2 \phi_{21} \propto i_1$$

Or, $N_2 \phi_{21} = M_{21} i_1 \quad 4.3.6$

Similarly a change in current in coil 2 will set up a flux linkage in coil 1 which is

$$N_1 \phi_{12} = M_{12} i_2 \quad 4.3.7$$

In general $M_{21} = M_{12} = M$.

Here M is known as the mutual inductance or coefficient of mutual inductance between two coils. The induced emf in the coil 2 due to change in the current in the coil 1 is

$$E_2 = -M \frac{di_1}{dt} \quad 4.3.8$$

$$\text{Or, } M = \frac{E_2}{\left| \frac{di_1}{dt} \right|} \quad 4.3.9$$

Thus we can define M from equation 4.3.6 and 4.3.9 as

- i) The mutual inductance between two coils is numerically equal to the magnetic flux linked with one coil due to unit current in the other.
- ii) The emf induced in one coil when the rate of decrease of current in the other coil is unity.

M depends on the closeness of two coils, their orientations and the number of turns of both coils.

Unit of inductance is Henry.

Coefficient of coupling:

From equation 4.2.6 and 4.2.7,

$$M_{12}M_{21} = M^2 = N_1N_2\phi_{12}\phi_{21}/i_1i_2 \quad 4.3.10$$

If a fraction of ϕ_1 is linked with coil 2 then

$$\phi_{21} = k_1\phi_1$$

Similarly $\phi_{12} = k_2\phi_2$

Therefore, $M_{12} = k_1k_2L_1L_2$

$$\text{or } M = \sqrt{k_1k_2} \sqrt{L_1L_2} = k\sqrt{L_1L_2} \quad 4.3.11$$

k is a constant known as coefficient of coupling. When total flux associated with one coil is linked totally with the other coil then

$$k_1 = k_2, \text{ and } k = 1.$$

Capacitance:

The property of a capacitor to store electricity is called its capacitance. Thus the capacitance is defined as the amount of charge required to create a unit potential difference between its plates.

If Q amount of charge is given to one of the two plates of a capacitor and if a potential difference of V volts is established between the two, then the capacitance is given by

$$C = \frac{Q}{V} \quad 4.3.12$$

Unit: The unit of capacitance is coulomb/volt called Farad.

Farad: It is the capacitance of a capacitor which requires a charge of one Coulomb to establish a potential difference of one volt between the plates. One Farad is actually large enough for practical purpose, Hence smaller unit like micro Farad, pico Farad, nano Farad are used.

1 micro Farad equals to 10^{-6} Farad.

Impedance:

For an alternating current circuit, the impedance takes part of resistance. Unlike resistance impedance is a complex quantity. It has a resistive part and a phase part. The phase of the complex impedance is the phase shift between current and voltage. Thus impedance is defined as

$$Z = R + jX$$

Where R is the resistance and it is real. The imaginary part X is called the reactance of the circuit. For LCR series circuit

$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right) \quad 4.3.13$$

Where, ωL is the inductive reactance and $\frac{1}{\omega C}$ is the capacitive reactance. The magnitude of Z is given by

$$|Z| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \quad \text{and } 4.3.14$$

$$Z = |Z| \exp^{i\theta} \quad 4.3.15$$

θ being the argument of Z shown in the fig 4.7 below.

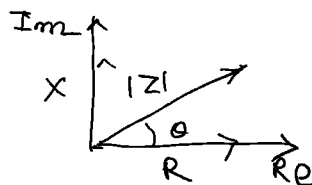


Fig 4.7

4.4 Operation of transformers

Transformers are electrical devices used to transfer electrical energy by means of changing magnetic field. It essentially consists of two magnetically coupled coils. One of them is called primary coil with resistance R_1 and inductance L_1 and the other is called secondary with resistance R_2 and inductance L_2 . In a transformer, the amount of electrical power is transferred from one winding to the other via the magnetic circuit. If the secondary output voltage is greater than the primary input the transformer is called as step up transformer. But when the output secondary voltage is less than the input primary voltage, the transformer is known as step down transformer.

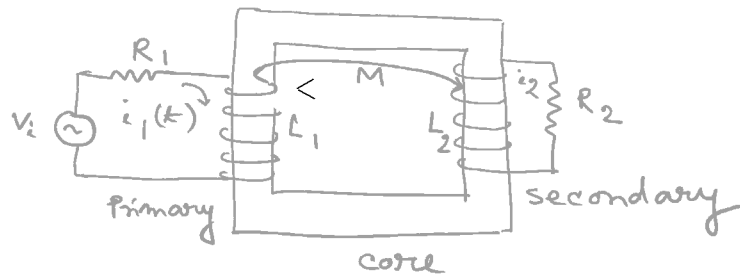


Fig 4.8

Theory:

Fig shows the circuit diagram of a transformer. Let us consider an ideal transformer when there is no leakage of magnetic flux or loss of energy. In such case let i_1 and i_2 be the instantaneous current in primary and secondary coil when the input alternating voltage represented by $V = V_1 \cos \omega t$ is applied across the primary. Now the instantaneous emf equations will be

$$R_1 i_1 + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} = v_1 \quad \text{and} \quad 4.4.1$$

$$R_2 i_2 + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} = 0 \quad 4.4.2$$

Here R_1 is the resistance of primary coil and R_2 denotes the resistance of the secondary coil including load.

$$\text{Let } v_1(t) = V_1 e^{j\omega t}, \quad i_1(t) = I_1 e^{j\omega t}, \quad i_2(t) = I_2 e^{j\omega t}$$

Then equations 4.4.1 and 4.4.2 reduces to

$$(R_1 + j\omega L_1)I_1 + j\omega M I_2 = V_1 \quad 4.4.3$$

$$j\omega M I_1 + (R_2 + j\omega L_2)I_2 = 0 \quad 4.4.4$$

From equation 4.4.4

$$I_2 = \frac{-j\omega MI_1}{R_2 + j\omega L_2}, \quad 4.4.4$$

and from equation 4.4.3,

$$(R_1 + j\omega L_1)I_1 = \frac{\omega^2 M^2 I_1}{R_2 + j\omega L_2} = V_1 \quad 4.4.5$$

After simplification we get $I_1 = \frac{V_1}{R_1' + j\omega L_1'}$ 4.4.6

Where $R_1' = R_1 + \frac{\omega^2 M^2 (R_2)}{R_2^2 + \omega^2 L_2^2}$, and 4.4.7

$$L_1' = L_1 \frac{\omega^2 M^2 L_2}{(R_2)^2 + \omega^2 L_2^2} \quad 4.4.8$$

Here R_1' and L_1' are called effective resistance and effective inductance of the primary respectively. The quantity $\frac{\omega^2 M^2 (R_2 + R_L)}{(R_2)^2 + \omega^2 L_2^2}$ is called the reflected resistance from the secondary to the primary and $\frac{\omega^2 M^2 + L_2}{(R_2)^2 + \omega^2 L_2^2}$ is the reflected inductance from the secondary to the primary. Thus effective primary resistance is increased and the effective primary inductance is decreased. Now from equation 4.2.6 and 4.2.4 the secondary current is given by,

$$I_2 = \frac{-j\omega M V_1}{(R_1' + j\omega L_1')(R_2 + j\omega L_2)} \quad 4.4.9$$

For an ideal transformer one has zero loss, primary and secondary impedance much larger than the connected reactance and no magnetic leakage. Therefore for an ideal transformer, assuming ωL_2 large compared to R_2 we can write equation 4.4.7 and 4.4.8 as

$$R_1' = R_1 + \frac{M^2 R_2}{L_2^2} \quad \text{and} \quad 4.4.7a$$

$$L_1' = L_1 - \frac{M^2}{L_2} \quad 4.4.8a$$

If there is no magnetic leakage, coefficient of coupling is one and we can write $M = \sqrt{L_1 L_2}$, then

$$R'_1 = R_1 + \frac{L_1 R_2}{L_2} \quad 4.4.7b$$

$$\text{and } L'_1 = 0 \quad 4.4.8b$$

This means when there is no magnetic leakage the primary inductance is effectively zero which means the effective impedance across the primary source of supply is purely resistive and is given by $R'_1 = R_1 + \frac{L_1 R_2}{L_2} = R_1 + \left(\frac{N_1}{N_2}\right)^2 R_2$ as $L_1 \propto N_1^2$, $L_2 \propto N_2^2$; N_1 and N_2 are the number of turns of the primary and secondary coils respectively.

In practice primary and secondary resistances are zero and a load R_L is considered. Then,

$$R'_1 = \left(\frac{N_1}{N_2}\right)^2 R_L \quad 4.4.10$$

Voltage and Current transformation ratio:

$$\text{We have } I_2 = \frac{-j\omega M I_1}{Z_2}$$

For ideal transformer

$$\left|\frac{I_2}{I_1}\right| = \frac{\omega M}{Z_2} = \frac{\omega M}{\sqrt{R_2^2 + \omega^2 L_2^2}} \approx \frac{M}{L_2} = \sqrt{\frac{L_1}{L_2}} = \frac{N_1}{N_2} \quad 4.4.11$$

If V_2 be the voltage across the load R_2 in the secondary, then since $I_2 = \frac{-j\omega M V_1}{Z_1 Z'_2}$,

$$V_2 = \frac{-j\omega M V_1}{Z_1}$$

Therefore,

$$\left|\frac{V_2}{V_1}\right| = \frac{\omega M}{\sqrt{R_1^2 + \omega^2 L_1^2}} \approx \frac{M}{L_1} = \frac{N_2}{N_1} \quad 4.4.12$$

$\frac{N_2}{N_1}$ is called the secondary to primary turns ratio.

Step down transformer: If $N_1 > N_2$, then $V_1 > V_2$. Such a transformer is known as step down transformer.

Step up transformer: When $N_2 > N_1$, then $V_2 > V_1$. Such a transformer is known as step up transformer.

For the ideal case the ratio of the primary to the secondary current is given by

$$\left| \frac{I_1}{I_2} \right| = \sqrt{\frac{L_2}{L_1}} = \frac{N_2}{N_1}$$

So that we get

$$|V_1| |I_1| = |V_2| |I_2|. \quad 4.4.13$$

This shows that for an ideal transformer output power equals input power, or in other words energy is conserved.

Transformer losses:

A practical transformer is always associated with some energy losses and output power. These losses are

Copper losses: It is the electrical power lost as heat as a result of circulating currents around transformer copper windings of primary and secondary. This loss is due to Joule heating. Copper losses can be reduced by making the resistance of primary and secondary coil small.

Iron (or core) loss: This is due to hysteresis and eddy current heating of the core. Eddy current losses are reduced by using laminated core of laminated sheets of soft iron for audio frequency transformer. Hysteresis loss is reduced by choosing a core material having small hysteresis loop area.

Flux leakage or magnetic leakage: This is due to the leakage of magnetic flux between primary and secondary. Iron core may be used to increase coupling coefficient thereby reducing magnetic flux leakage. Radio frequency transformer uses ferrite core having high permeability and low electrical conductivity.

Transformer efficiency: Because of the various types of losses in a practical transformer, output power is small than the input power. The efficiency of a transformer is defined as the power output in the secondary winding to the power input in the primary windings. Thus

$$\text{Efficiency } \eta = \frac{\text{Output Power from secondary}}{\text{Power delivered by the source}} \times 100\%$$

At full load the efficiency of a transformer is in between 94% to 96% which is quite good. For a transformer operating at a constant voltage and frequency with a very high capacity, the efficiency may be as high as 98%. In properly designed transformer an efficiency of 99% is achievable. The rating of a transformer is usually expressed in Volt-Ampere This is because copper loss depends on current, iron loss depends on voltage and total transformer loss depends on current x voltage and not on the phase angle which is the usual case for AC circuit.

Types of transformer:

Transformers are classified according to frequency and structure. Depending upon frequency, it is classified as i) mains frequency transformer ii) audio frequency transformer and iii) radio frequency transformer. On the basis of structural dependence it is classified as i) core type (single magnetic circuit), ii) shell type (double magnetic circuit) and iii) berry type (distributed magnetic circuit).

Uses: Some of the common uses of transformers are;

1. To step up or step down ac voltage in electrical power distribution for industrial and domestic applications.
2. For the construction of power supplies.
3. Impedance transformer is used for impedance matching between two independent circuits to get maximum power.
4. Current transformers are used to measure large alternating current.
5. For long distance power transmission.

Auto transformer: It consists of a single winding only, part of which is common to both primary and secondary.

4.5 Summary

Generator is used to convert mechanical energy into electrical energy. Normally we use AC generator in daily life. Another important electrical devices for distribu-

tion of electricity in domestic life is transformer which are two types. One is step up and other is step down.

4.6 Short questions

1. Based on how the field magnets are energised classify different types of generator.
2. Write down different parts of a generator.
3. What are different types of losses in a generator? Define efficiency of a generator.
4. What is meant by capacitance of a capacitor and inductance of an inductor?
5. What is meant by reactance and impedance of an ac circuit?
6. What is a transformer? Give a neat diagram of an ideal transformer.
7. What is meant by step up and step down transformer? Is the output power in a step up transformer greater than the input power?
8. Show that in an ideal transformer the ratio of output voltage to the input voltage is equal to the ratio of number of turns of secondary to the number of turns in primary.
9. Write down different types of losses associated with a transformer.
10. When a resistance of 10 Ohm is connected to the secondary of an ideal step down transformer with turns ratio 5:1, calculate effective primary resistance.
Ans 250 Ohm.

Unit 5 □ Electric Motors

Structure

5.0 Objectives

5.1 Introduction

5.2 AC Motors

5.2.1 Rotating magnetic field

5.2.2 Couple acting on a small coil placed in a rotating magnetic field

5.2.3 Types of induction motor

5.3 DC Motors

5.4 Interfacing DC or AC sources to control heaters and motors

5.5 Speed and power of AC motor

5.6 Summary

5.7 Short questions

5.0 Objective

In this chapter you gather knowledge on the following topics

- Electrical motors(AC and DC Motors)
- Different kind of Induction motor
- Power in a Motor

Electrical Motors:

An electrical motor is an electromechanical device which converts electrical energy into mechanical energy. There are two types of motors; DC motor and AC motor.

5.1 Introduction

Motor is an electrical device which converts electrical energy into mechanical energy. There are two types of motors: AC motor and DC motor. As it is an important device, a thorough discussion about its principle is required.

5.2 AC Motors

Induction motor:

In DC motor current is supplied to both the stator and to the rotor but in AC motor or induction motor we give only one supply which is in the stator and current is induced in the rotor by the rotating magnetic field. At first we see how an induction motor works. The motion of a conductor in a rotating magnetic field has been used in the construction of induction motors. This motor is comparatively simple in construction, low in cost, robust and efficient. The motor has a stationary part called the stator and a rotating part named the rotor. The stator carries a polyphase (two or three) winding connected to the supply. The polyphase currents generate a rotating magnetic field. The magnetic flux of the stator linked with the rotor changes with time and hence currents are induced in the rotor conductors. The rotor will experience a driving couple and the rotor rotates along with the stator field. The magnitude of the induced rotor current depends on the relative velocity of the rotor with respect to the stator field.

There are two types of rotor winding, the squirrel cage and the phase wound. In squirrel cage there are a number of copper bars threaded through slots in a laminated rotor core, with their ends connected in strong copper end rings. This type is used only for comparatively small motors. The phase wound type is provided with distributed windings. The separate phases are generally connected in star and the free ends connected each to one of three insulated slip rings mounted on the motor shaft.

The angular speed of the rotor can never be equal to that of the rotating magnetic field. For in that case there will be no relative angular velocity and no torque will act on the rotor. The difference between the speed of the rotating field and the speed of the rotor is called the slip. Such type of motor is known as asynchronous motor.

5.2.1 Rotating magnetic field

A rotating magnetic field is one in which the magnitude of the field remains constant but its direction rotates at a constant rate about a fixed axis. It can be produced with stationary coils supplied with in general three or polyphase alternating current.

a) Two phase supply:

Let us consider two coils AB and CD carrying alternating current and placed at right angles to each other. The current in these coils are of equal frequency and

amplitude but differ in phase by $\pi/2$. The magnetic field due to this current carrying coil will be in phase with the currents and will be in the direction normal to the plane of the respective coils. Thus the magnetic field along OX and OY at any instant of time t are given respectively by

$$B_1 = B_0 \sin(\omega t) \text{ and } B_2 = B_0 \sin\left(\omega t - \frac{\pi}{2}\right) \quad 5.2.1.1$$

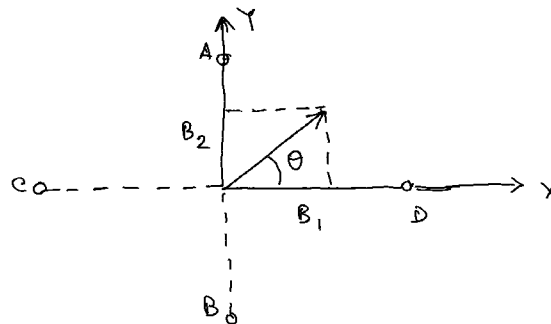


Fig 5.1

The magnitude of the resultant magnetic field is given by

$$B = \sqrt{B_1^2 + B_2^2} = B_0 \quad 5.2.1.2$$

Which is constant, independent of time and makes an angle θ with B_1 or X axis, so that

$$\tan\theta = \frac{B_2}{B_1} = \tan\left(\omega t - \frac{\pi}{2}\right) \text{ or } \theta = \omega t - \frac{\pi}{2}. \quad 5.2.1.3$$

Thus θ increases with time and the resultant magnetic field B rotates with a uniform angular velocity ω in the counter clockwise direction. When B_1 lags B_2 by $\pi/2$, the rotation will be clockwise.

b) Three phase supply: Three identical coils AB, CD and EF are arranged 120° apart, as shown in the figure 5.2. The magnetic field produced at the centre O by the coils AB, CD and EF are directed along OP, OQ and OR respectively. Then

$$\begin{aligned} B_1 &= B_0 \sin \omega t \\ B_2 &= B_0 \sin (\omega t - 120^\circ) \text{ and} \\ B_3 &= B_0 \sin (\omega t - 240^\circ), \end{aligned}$$

where, B_0 and ω are respectively the amplitude and angular frequency of each magnetic field. Resolving the fields along OP and perpendicular to it we also get a resultant magnetic field

$$B = \sqrt{X^2 + Y^2} = \frac{3}{2}B_0$$

$$\text{Here } X = B_1 + B_2 \cos 120^\circ + B_3 \cos 240^\circ = \frac{3}{2}B_0 \sin \omega t$$

$$\text{And } Y = 0 + B_2 \sin 120^\circ + B_3 \sin 240^\circ = -\frac{3}{2}B_0 \cos \omega t$$

The angle θ between B and OP at any time t is given by

The angle between B and OP at any time t is given by

$$\tan \theta = \frac{-\frac{3}{2}B_0 \cos \omega t}{\frac{3}{2}B_0 \sin \omega t} = \tan(\omega t - 90^\circ)$$

So that $\theta = \omega t - 90^\circ$ and it increases with time. The resultant magnetic field B rotates with uniform angular velocity in an anti clockwise direction.

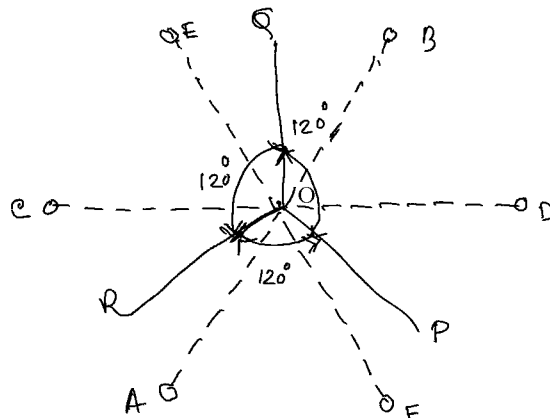


Fig 5.2

5.2.2 Couple acting on a small coil placed in a rotating magnetic field

When a small coil of N turns and effective area A is placed in the rotating magnetic field, with its centre coinciding at the centre of the rotating magnetic field an induced current will be produced in the coil. According to Lenz's law the direction of induced current will be such as to oppose the relative motion between the coil and the magnetic field and as a result a couple acts on the coil tending to rotate the coil

in the direction of the field. At any instant t the flux linkage with the coil is

$$\Phi = NAB \sin \omega t \quad 5.2.2.1$$

where ωt is the angle between the direction of magnetic field and the plane of the coil.

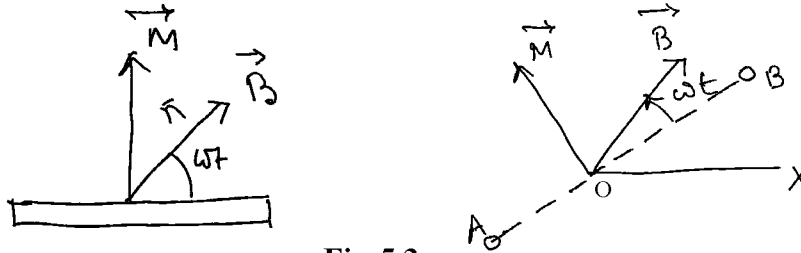


Fig 5.3

The induced emf in the coil is

$$E = \frac{d\Phi}{dt} = NAB\omega \cos(\omega t - P). \quad 5.2.2.2$$

Corresponding induced current in the circuit with resistance R and self inductance L is given by

$$i = \frac{NAB\omega}{\sqrt{R^2 + \omega^2 L^2}} \cos(\omega t - P - \alpha) \quad 5.2.2.3$$

Where $\tan \alpha = \frac{\omega L}{R}$, α is the phase lag between emf and current.

Now the coil will behave like a magnetic dipole of moment $\vec{M} = NiA\vec{n}$. The torque acting on the coil will turn it into the direction of \vec{B} and the moment of the couple is

$$\vec{\tau} = \vec{M} \times \vec{B} = \check{k} MB \sin\left(\frac{\pi}{2} - \omega t\right), \check{k} \text{ is a unit vector normal to the plane containing } \vec{M} \text{ and } \vec{B}$$

$$\therefore \tau = \check{k} NiAB \cos \omega t$$

$$= \check{k} \frac{N^2 A^2 B^2 \omega}{\sqrt{R^2 + \omega^2 L^2}} \cos(\omega t - P - \alpha) \cos \omega t \quad 5.2.2.4$$

The average torque acting on the coil is

$$\begin{aligned}\tau_{av} &= -\frac{N^2 A^2 B^2 \omega}{2\sqrt{R^2 + \omega^2 L^2}} \cos\alpha \\ &= -\frac{N^2 A^2 B^2 \omega R}{2(R^2 + \omega^2 L^2)}\end{aligned}\quad 5.2.2.5$$

The torque tends to rotate the coil in the direction of rotating magnetic field. The angular velocity of the coil can never be equal to that of the rotating magnetic field, because in that case $\omega = 0$ and $\tau_{av} = 0$. Now from equation 5.2.2.5, $\tau_{av} = 0$, when $\omega = 0$ and $\omega = \infty$. When the coil is free to rotate, its angular velocity in the direction of the field of rotation increases till the rate of doing work against friction is equal to the rate of work done by rotating field. In the steady state the coil moves with a constant angular velocity such that the rate of doing work by the torque becomes equal to the rate of all type of frictional forces.

$$\text{Now } \frac{d\tau_{av}}{d\omega} = \frac{N^2 A^2 B^2 R}{2} \frac{d}{d\omega} \frac{\omega}{(R^2 + \omega^2 L^2)} = 0, \text{ gives } \omega L = R \text{ and } \frac{d^2\tau_{av}}{d\omega^2} \text{ is negative.}$$

This gives is maximum at $\omega = \frac{R}{L}$ and value of

$$\tau_{av\max} = \frac{N^2 A^2 B^2}{4L}\quad 5.2.2.6$$

Slip and Slip frequency

The difference between the speed of the rotating field and the speed of the rotor is called a slip. The frequency of the current induced in the rotor windings depends on the slip and is known as slip frequency.

5.2.3 Types of induction motor

Single Phase:

The working of any electrical motor whether AC or DC, requires fluxes to produce torque as the interaction between fluxes. If AC supply flows through the windings of the stator of single phase motor, since the pulsating magnetic field can be assumed as two oppositely rotating magnetic field, there will be no torque on the rotor and hence the motor does not run. After giving the supply if the rotor is made

to rotate in either direction by an external force, then the motor will start to run. This problem is solved by making the stator windings into two windings; one is the main winding and the other is auxiliary winding. When alternating current flows through both the windings and a phase difference is created by some means the resulting flux is rotating in nature.

Like any other electrical motor a single phase induction motor as discussed earlier has two main parts, a stator and a rotor.

Stator:

The stator is the stationary part of induction motor. It has laminated stamping to reduce eddy current losses on its periphery and also made up of silicon steel to reduce hysteresis loss.

Rotor:

The rotor is the rotating part of the motor and is of squirrel cage type. The rotor connects the load through the shaft. The squirrel cage rotor is cylindrical and has slots all over the boundary. The rotor conductors are aluminium, brass or copper bars and are placed into the slots on the periphery. The copper or aluminium rings permanently short the rotor conductors. These are called end rings.

Single phase induction motors are classified as

1. Split phase induction motor (SPIM);
2. Capacitor start induction motor (CSIM);
3. Capacitor start capacitor run induction motor (CSCRIM);
4. Permanent split induction motor (PSIM);
5. Shaded pole induction motor.

We shall discuss first two types of single phase induction motor (SPIM).

1. Split Phase induction motor (SPIM):

Here in addition to the main winding or running winding, the stator carries another winding called auxiliary winding or starting winding. To create a rotating magnetic field there should be a phase difference between the two windings and this is done by making running winding inductive in nature and adding a high resistance in the starting winding.

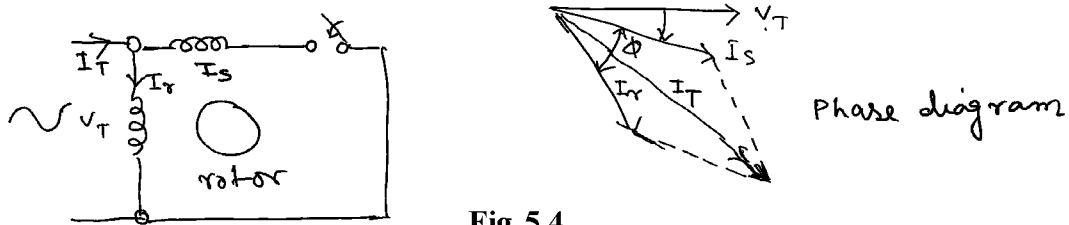


Fig 5.4

Let I_r is the current flowing through the main winding and I_s is the current flowing in the starting winding and V_T is the alternating voltage. In highly resistive winding the current is almost in phase with the voltage and in inductive winding the current lags behind the voltage by large angle. The resultant of these two currents I_T produces rotating magnetic field. In split phase induction motor the starting and main current get split from each other and hence the name split phase motor. A centrifugal switch is connected in series with auxiliary winding. When the motor attains a speed upto 75 to 80% of the synchronous speed this switch disconnects the auxiliary winding from the main current.

2. Capacitor Start Induction motor (CSIM):

In case of split phase induction motor we use resistance for creating phase difference. For capacitor start induction motor we use capacitor for this purpose. With starting winding a capacitor is connected so the current flowing in the capacitor leads the applied voltage by some angle ϕ_s . The running winding is inductive in nature, so the current flowing in the running winding lags behind the applied voltage by an angle ϕ_m . A large phase difference occurs between these two currents. The resulting current I will produce a rotating magnetic field. The phase angle difference is very large, the torque produced by these motors are high. In the starting winding circuit a centrifugal switch is provided which disconnects the starting winding when the motor attains a speed upto 75% to 80 % of the synchronous speed.

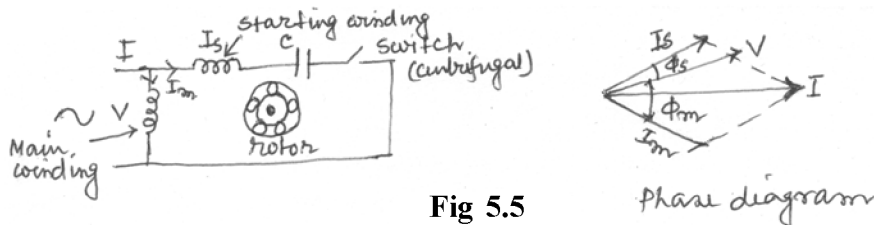


Fig 5.5

Application:

Split phase induction motors are used in fans, blowers, centrifugal pumps

washing machine etc. These motors are available upto 1/20 to 1/2KW. CSIM induction motors are used in conveyers, grinder, air conditioner etc. They are available upto 6 KW.

Three Phase:

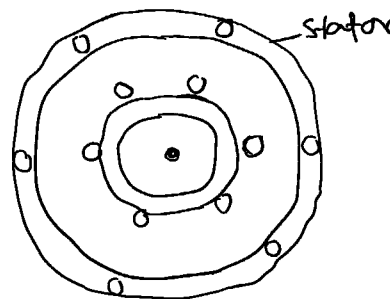
The most widely used induction motor is a three phase induction motor. This type does not require an additional starting device. The motor consists of two major parts; a stator and a rotor.

Stator:

The stator is made up of number of slots to construct a 3 phase winding circuit which is connected with 3 phase AC source. The 3 phase windings are arranged in such a manner in the slots that they produce a rotating magnetic field when the 3 phase AC supply is switched on.

Rotor:

The rotor is squirrel cage type. It consists of a cylindrical laminated core with parallel slots that can carry conductors. The conductors are made of copper or aluminium bars fitted in each slot and are short circuited by end rings. To reduce magnetic humming noise the slots are not made exactly parallel to the axis of the shaft but slotted a little skewed.



schematic diagram
of a simple induction
motor

Fig 5.6

Working Principle:

The production of rotating magnetic field has been discussed earlier in three phase AC supply. Thus when we connect primary windings of the stator to 3 phase AC source, it establishes a rotating magnetic field. The rotor is placed in the rotating

magnetic field and an emf is induced in the rotor copper bar and current flows through the rotor conductor. As per Lenz's law the rotor will experience a torque and will rotate in the same direction to reduce the cause. The magnitude of the torque produced in the rotor has been derived earlier. The rotor speed will increase to reduce the relative velocity. In the steady state the rotor coil moves with a constant angular velocity such that the rate of doing work by the torque becomes equal to the rate of all kinds of frictional and other causes.

It was also discussed earlier that the rotor speed should not reach the synchronous speed produced by the stator. If the speeds are equal there would be no such relative angular velocity and no torque will be generated. Thus the rotor cannot reach the synchronous speed. The difference between the stator and rotor speed is called the slip.

The advantage of three phase induction motor is

1. Self starting
2. Less armature reaction and brush sparking
3. Robust in construction
4. Economical.

5.3 DC Motors

Basic Design:

When a conductor carrying a current I is placed in a magnetic field B , a force acts on the conductor. If the conductor is a coil of N turns, then the torque on the coil is

$$\tau = iNAB \sin \theta$$

Where A is the area of the coil and θ is the angle which the normal to the plane of the coil makes with the direction of magnetic field. Let the ends of the coil is connected to each half of a split ring AB and current is passed through the brushes $B1$ and $B2$ which are attached to each split ring as diameter. When $\theta = 0$, the plane of the coil is vertical and no torque will act on the coil (armature). After the vertical position of the coil current passes through opposite direction due to split ring, and the torque acts in the same direction. Thus the coil rotates in the same direction.

There are two positions of the coil with no torque. If the coil (armature) has sufficient inertia and the frictional forces are small, the angular momentum gained earlier carries it through the zero torque position.

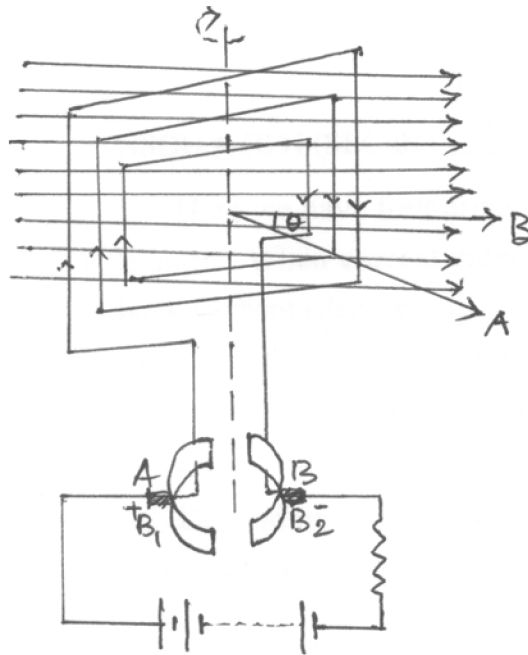


Fig 5.7

Thus the armature rotates in same direction with two positions of no torque. In this way electrical energy is converted into mechanical energy which is the principle of motor.

The motion of a motor with a single coil and two poles is not continuous. In practice the single coil is replaced by several coils inclined equally with each other. As an ex. consider the continuous drum winding as in the fig. 5.8 below.

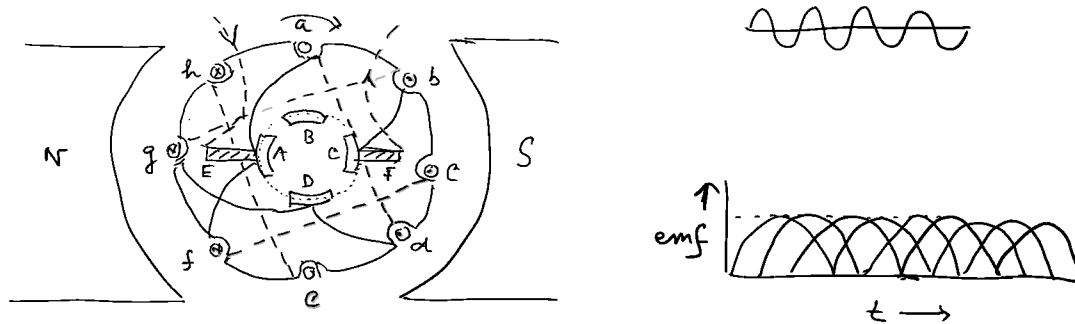


Fig 5.8

Here we have four armature conductors with source of emf applied to the brushes E and F. When current enters E and leaves F, the currents in b, c and d will be from back to front (denoted by dot) and in f, g and h from front to back (denoted by cross). In such case b, c and d experience an upward force and f, g and h will experience downward force which results the rotation of the coil in anticlockwise direction. By increasing the number of conductors we can get a steady motion of the motor.

Depending upon the method of excitation the motors are of three types. They are series wound; shunt wound and compound wound motors.

Efficiency: Electrical efficiency is given by $\frac{\text{Mechanical energy obtained}}{\text{Electrical energy supplied}} = \frac{Ei}{Vi}$

Here V is the potential applied to the brushes and E is the back emf. It can be shown that the motor develops the maximum mechanical power when the armature resistance or the armature current is such that the back emf is equal to one half of the applied emf.

5.4 Interfacing DC or AC sources to control heaters and motors

A protective relay is a device that detects the fault and initiates the operation of the circuit breaker (CB) to isolate the defective element from the rest of the system. The fault condition (one or more of the quantities, voltage, current, frequency and phase angle) are conveyed to protective relay through signal.

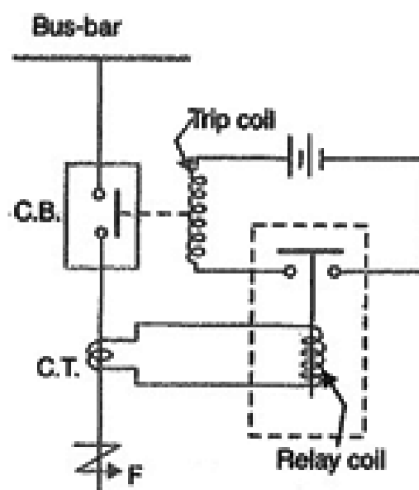


Fig. 5.9 Protective relay circuit

Protective relaying is used in electrical substations to give an alarm to cause prompt removal of any element of the power system from service when the element behaves abnormally.

Working:

When short circuit occurs at the point F on the transmission line, the current flowing in the line increases to a large value and as a result heavy current flows through the relay coil causing the relay to operate by closing its contacts. This closes the trip circuit of the breaker, making CB open and thus isolating the fault section from the rest of the system.

5.5 Speed and power of AC motor

Speed of AC motor:

AC motors are built to run at specific speeds regardless of their design or manufacturer. The speed of an AC motor is dependent on the number of poles it has and the line frequency of the power supply, not on its voltage. Common AC motor units are constructed with either two or four poles. A magnetic field is created in the stator poles that induce resulting magnetic fields in the rotor which follow the frequency of the changing magnetic field in the stator.

$$\text{Speed} = 120 \times \text{frequency (Hz)} / \text{poles of the motor}$$

Two pole AC motors operating at 60 Hz will always run at approximately 3600 rpm, and four pole AC motors will have speeds around 1800 rpm.

The speed of an AC motor will be slightly lower—because there is a certain amount of slip that must be present for the motor to produce torque. The rotor will always rotate slower than the magnetic field of the stator. This produces the torque to get an AC motor running. The difference between the synchronous speeds of the stator (3600 and 1800 rpm) and the actual operating speed is called slip.

A control can be used to alter the speed of a three phase AC motor by increasing or decreasing the frequency that is sent to the motor, causing it to speed up or slow down. However, this ability to alter the speed isn't typically the case for single phase AC motors. These motors are plugged directly into a standard wall outlet and operate

using the set frequency available. An exception to this rule of thumb would be a ceiling fan that runs using single phase AC motor, but has

Slip

The difference between synchronous speed and actual speed is called **slip**, and loading the motor increases the amount of slip as the motor slows down slightly. Even with no load, internal mechanical losses prevent the slip from being zero.

The speed of the AC motor is determined primarily by the frequency of the AC supply and the number of poles in the stator winding, according to the relation:

$$N_s = 120 \times F/p$$

Where

N_s = Synchronous speed, in revolutions per minute

F = AC power frequency

p = Number of poles per phase winding

Actual RPM for an induction motor will be less than this calculated synchronous speed by an amount known as *slip*, that increases with the torque produced. With no load, the speed will be very close to synchronous. When loaded, standard motors have between 2–3% slip. The slip of the AC motor is calculated by:

$$S = (N_s - N_R)/N_s$$

Where

N_R = Rotational speed, in revolutions per minute.

S = Normalised Slip, 0 to 1.

As an example, a typical four-pole motor running on 60 Hz might have a nameplate rating of 1725 RPM at full load, while its calculated speed is 1800 RPM. The speed in this type of motor has traditionally been altered by having additional sets of coils or poles in the motor that can be switched on and off to change the speed of magnetic field rotation.

Power of an electrical motor

In an electric motor, the mechanical power is defined as the speed times the torque. Mechanical power is typically defined as kilowatts (kW) or horsepower (hp) with one watt equals to one joule per second.

5.6 Summary

AC motor is one of the useful devices which we use in our daily life and most common motor is induction motor. DC motors are used in small devices such as computer, electronic gadget etc.

5.7 Short questions

1. What is meant by rotating magnetic field? How it is generated by a two phase or three phase electric supply?
2. If a small coil is placed in a rotating magnetic field, calculate the torque acting on it.
3. How principle of rotating magnetic field is utilised in the construction of induction motor?
4. What is meant by slip and slip frequency of induction motor?
5. What are different classifications of single phase induction motor?
6. Describe Capacitor start induction motor (CSIM).
7. Write down the advantage of three phase induction motor.
8. Briefly describe construction of DC motor.
9. What is meant by speed of an ac motor?
10. How power is defined in an electrical motor?

Unit 6 □ Solid State devices

Structure

- 6.0 Objective
- 6.1 Introduction
- 6.2 Resistors, Inductors, and capacitors
- 6.3 Components in series or in shunt
- 6.4 Diodes and rectifiers
 - 6.4.1 P-N junction
 - 6.4.2 Current flow in junction diode
 - 6.4.3 Diodes in series and in parallel
 - 6.4.4 Different Types of diode
 - 6.4.5 Rectifiers
- 6.5 Response of inductors and capacitors with DC or AC source
 - 6.5.1 Growth and Decay of Current in Series LR Circuit
 - 6.5.2 Charging and discharging of a capacitor in DC circuit
 - 6.5.3 AC Source
- 6.6 Summary
- 6.7 Short questions

6.0 Objective

In this chapter you gather knowledge on the following topics

- Resistors, Inductors, and capacitors and its use in circuit
- PN junction diode and its application in rectifier circuit.
- Growth and decay of current.

6.1 Introduction

Inductors and capacitors and their combinations are used in many electrical devices. In solid state devices diode is an important tool for rectification of AC to DC. Response of inductors and capacitors in DC and in AC source is different from those for resistors.

6.2 Resistors, Inductors, and capacitors

a. Resistor:

A resistor is a passive two terminal electrical component which can offer electrical resistance as a circuit element. In electronic circuits it is used to reduce current flow, adjust signal levels or can divide voltages. Fixed resistors have resistances that can only change slightly with temperature. To adjust circuit elements (volume control) or as sensing devices for heat, light, humidity etc variable resistors are used. The resistance of a resistor is given by Ohm's law which is expressed as $V = IR$, where V is the voltage across a resistor carrying a current I . The schematic symbol of resistor is as follows.

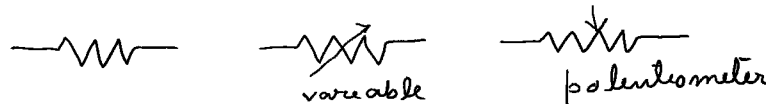


Fig 6.1

Practical resistors may not be ideal. It may have some sort of inductance and stray capacitance. Though this has no effect in direct current circuit but it affects alternating current circuit. The SI unit of resistance is Ohm.

b. Inductors:

An inductor also called a choke is a passive two terminal electrical component which stores energy in a magnetic field when current passes through it. It consists of a coil of insulated wire wound around a core. When current-flows through an inductor changes, the associated magnetic flux also changes and this induces an emf in the conductor (according to Faraday's law of electromagnetic induction). According to Lenz's law this induced emf opposes the change of current. Thus $E = L \frac{di}{dt}$. L is called coefficient of self inductance. Inductors are used to block AC while allow DC to pass through it. Below are the symbols of inductors. Unit of inductance is Henry.



Fig 6.2

c. Capacitors:

Capacitors are also two terminal passive electronic components. It consists of two conducting surfaces separated by insulating material called dielectric. Capacitors

are used to store electrical charge or electrical energy by electrostatic stress in the dielectric medium, In general the conducting surface of a capacitor maybe in the form of circular or rectangular plates. They may be also of spherical or cylindrical type. When a parallel plate capacitor with plates A and B is joined across a battery, with A +ve and B -ve, there is momentarily flow of electrons from A to B. As a result a potential difference is established across the plates A and B. The capacitance of a capacitor is given by $C = Q/V$, where Q is the charge stored and V is the potential difference across the plates. Unit of capacitance is Farad or microfarad. Symbols of capacitor are shown below.

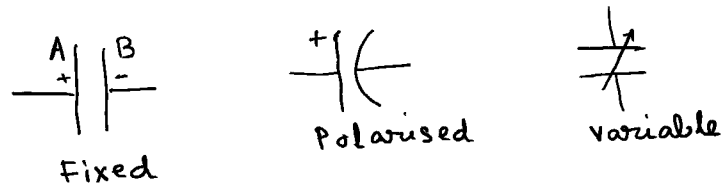


Fig 6.3

6.3 Components in series or in shunt

Inductance:

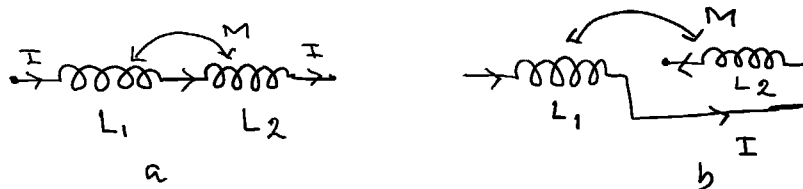


Fig 6.4

When two inductances L_1 and L_2 are in series as in fig 6.4a and 6.4b, and a current I is flowing through them, then the induced emf in coil 1 due to self inductance is

$$E_{11} = -L_1 \frac{dI}{dt} \tag{6.3.1}$$

Induced emf in coil 2 due to current I in coil 1 is

$$E_{21} = -M \frac{dI}{dt}, \tag{6.3.2}$$

where M is the mutual inductance between two coils 1 and 2.

Induced emf in coil 2 due to self inductance is

$$E_{22} = -L_1 \frac{dI}{dt} \quad 6.3.3$$

and the emf induced in coil 1 due to current I in coil 2 is

$$E_{12} = -M \frac{dI}{dt}. \quad 6.3.4$$

Total emf for fig 6.4a is

$$E = E_{11} + E_{22} + E_{21} + E_{12} = -(L_1 + L_2 + 2M) \frac{dI}{dt} \quad 6.3.5$$

Let L_{eq} be the equivalent inductance. Then

$$E = -L_{eq} \frac{dI}{dt} \quad 6.3.6$$

From eqn 6.3.5 and 6.3.6

$$L_{eq} = L_1 + L_2 + 2M \quad 6.3.7$$

For fig 6.4b

$$E = E_{11} + E_{22} - E_{21} - E_{12} \quad 6.3.8$$

$$\therefore L_{eq} = L_1 + L_2 - 2M$$

If $M = 0$ then

$$L_{eq} = L_1 + L_2 \quad 6.3.9$$

Parallel combination

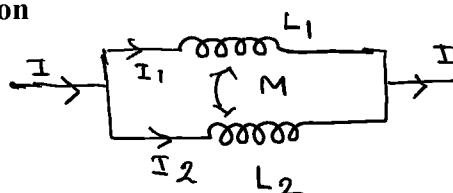


Fig 6.4c

As in the following fig, 6.4c I_1 current is passing through L_1 and I_2 current is passing through L_2 . Thus induced emf in coil 1 and in coil 2 are respectively

$$E_1 = -L_1 \frac{dI_1}{dt} - M \frac{dI_2}{dt} \quad 6.3.10$$

$$E_2 = -L_2 \frac{dI_2}{dt} - M \frac{dI_1}{dt} \quad 6.3.11$$

Since two coils are in parallel combination,

$$E_1 = E_2 = E$$

$$L_1 \frac{dI_2}{dt} + M \frac{dI_2}{dt} = L_2 \frac{dI_2}{dt} + M \frac{dI_1}{dt} = E \quad 6.3.12$$

By Cramer's rule

$$\frac{dI_1}{dt} = \frac{-E(L_2 - M)}{L_1 L_2 - M^2} \quad \text{and} \quad \frac{dI_2}{dt} = \frac{-E(L_1 - M)}{L_1 L_2 - M^2} \quad 6.3.13$$

$$\text{Now} \quad \frac{dI}{dt} = \frac{dI_1}{dt} + \frac{dI_2}{dt} = \frac{-E(L_1 + L_2 - 2M)}{L_1 L_2 - M^2} \quad 6.3.14$$

$$\therefore E = \frac{(L_1 + L_2 - 2M) dI}{(L_1 L_2 - M^2) dt} \quad 6.3.15$$

If L_{eq} be the equivalent inductance, then

$$E = -L_{eq} \frac{dI}{dt} \quad 6.3.16$$

Comparing eqn 6.3.15 and 6.3.16

$$L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M} \quad 6.3.17$$

Or, when mutual flux opposes self flux

$$L_{eq} = \frac{L_1 L_2 - M^2}{L_1 L_2 + 2M} \quad 6.3.17a$$

If $M = 0$,

$$L_{eq} = \frac{L_1 L_2}{L_1 + L_2} \quad 6.3.18$$

Capacitance:

Series combination:

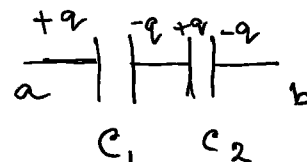


Fig 6.5a

Let C_1 and C_2 be the two capacitors connected in series. Let the p.d across a and b be V_{ab} . During charging same current flows through capacitors for same time, so that the capacitors acquire the same charge q . Now

$$V_1 = \frac{q}{c_1} \text{ and } V_2 = \frac{q}{c_2},$$

$$\text{Now, } V_{ab} = V_1 + V_2 = q \left(\frac{1}{c_1} + \frac{1}{c_2} \right) \quad 6.3.19$$

If C be the equivalent capacitance, then

$$V_{ab} = \frac{q}{c} \quad 6.3.20$$

$$\therefore \frac{1}{c} = \left(\frac{1}{c_1} + \frac{1}{c_2} \right) \quad 6.3.21$$

or, for n no. of capacitors,

$$\frac{1}{c} = \sum_1^n \frac{1}{c_i} \quad 6.3.21a$$

Parallel Combination:

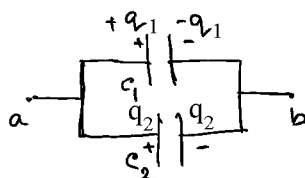


Fig 6.5b

If V_{ab} be the potential difference across the terminals a and b then the charges on two capacitors will be

$$q_1 = C_1 V_{ab} \text{ and } q_2 = C_2 V_{ab} \quad 6.3.22$$

Now total charge

$$q = q_1 + q_2 = (C_1 + C_2) V_{ab} \quad 6.3.23$$

If C be the equivalent capacitance, then

$$q = C V_{ab} \quad 6.3.24$$

$$C = C_1 + C_2 \quad 6.3.25$$

or

$$C = \sum_1^n C_i \quad 6.3.25a$$

6.4 Diodes and rectifiers

Diodes:

A diode is a two terminal electronic component with low resistance in one direction and high resistance in the other direction. Thus it conducts current mainly in one direction. Commonly used diode is semiconducting diodes. It is a p-n junction of semiconducting material (such as Si, Ge, GaAs) connected to two electrical terminals.

6.4.1 P-N junction

The p-n junction is the junction between p type semiconductor material say Ge doped with indium (In) and a n-type semiconductor material say germanium doped with antimony (Sb). The junction must be grown from a single crystal. Immediately after formation of the p-n junction, electrons from n type semiconductor diffuses across the junction leaving behind positive ions of impurity atoms (antimony) and reaches the p type acceptor material on the other side. At the same time positive holes from p-type material diffuse across the n-type (fig 6.6b). The build up of static charges due to ions produce an electric field and a potential barrier across the junction which forbids further electron hole diffusion. The charge density across the small region of about 10^{-4} cm in width across the junction is shown in fig 6.6c. The corresponding potential distribution is shown in fig 6.6c.

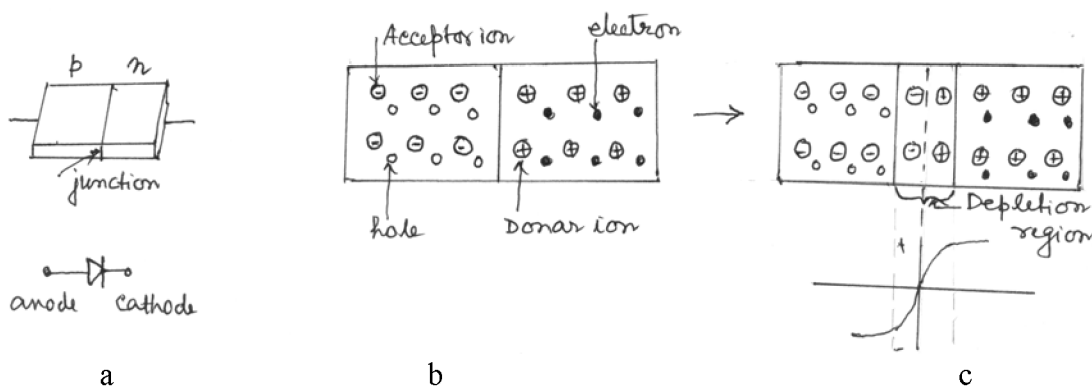


Fig 6.6

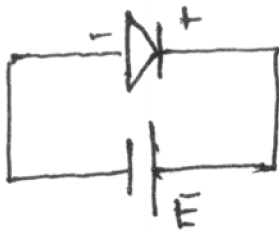
In the equilibrium condition when electron and holes diffusion is prevented by the electric field across the junction, the net current is zero. At the equilibrium the

Fermi level in the two semiconductor material, one p type and other n type becomes equal.

6.4.2 Current flow in junction diode

Reverse bias:

When a battery across a p-n junction is connected in such a way (-ve terminal to n-type and +ve to p- type) that the potential barrier is increased, then practically no current will flow. In practice there will be a small current due to a small amount of thermally generated electron -hole pairs formed and the electrons go across the junction to p-type and holes go to the n-type. This small current is known as reverse current. It reaches saturation at a few μ amp with a small applied p.d.



(a)

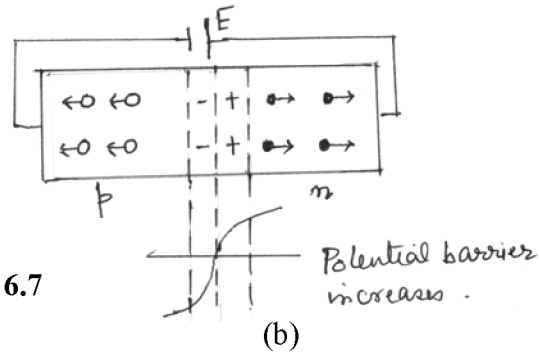
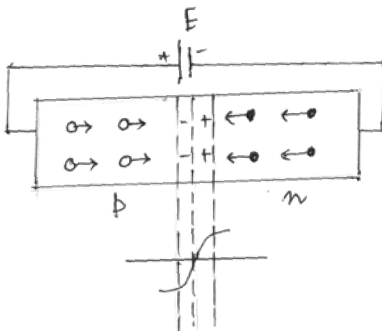


Fig 6.7

(b)

Forward bias:

If the polarity of the battery is such that the positive terminal is connected to n-type and the negative terminal connected to p-type, the potential barrier across the junction is reduced. So holes cross the junction from p type to n type and electrons across the junction from n-type to p-type. This forward bias causes considerable current to flow through the junction and hence to the external circuit. In this way diode or p-n junction has a rectifying property.



Potential barrier decreases

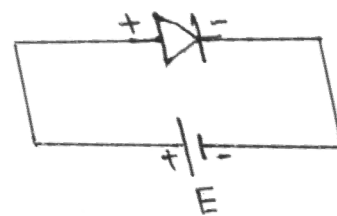
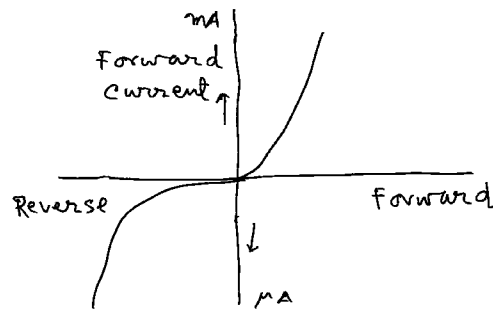


Fig 6.8

Current -Voltage Characteristics:**Fig 6.9**

The current voltage characteristic is shown in fig 6.9. The current in forward bias increase exponentially with V , the forward bias, accordingly

$$I = Ae^{\frac{Ve}{kT}} - I_0 \quad 6.4.1$$

Here e is the electronic charge, k is Boltzmann constant and T is absolute temperature and I_0 is reverse saturation current. When V is zero, I is zero, so $A = I_0$. Thus

$$I = I_0(e^{\frac{Ve}{kT}} - 1) \quad 6.4.1a$$

This equation holds when the applied voltage does not exceed the barrier potential (~ 0.1 to $0.2 V$). For values of V greater than the barrier voltage the relation between I and V is linear. This is the normal working portion of the characteristics (fig 6.9). Forward bias voltage must not be increased excessively which will burn out the diode.

With a reverse bias eqn 6.3.1a becomes

$$I = I_0(e^{\frac{Ve}{kT}} - 1) \quad 6.4.2$$

This shows that $I = I_0$ approximately when V is greater than about -0.1 volt. Therefore, reverse saturation current reaches with very small reverse voltage.

Zener effect:

When reverse voltage is very high there is a sharp rise of current and a breakdown of junction resistance occurs. This is known as Zener effect.

Diodes as shunts: When a device is vulnerable to reverse polarity of a signal or power supply, a diode in shunt position may be used to protect the circuit. When connected in parallel to the circuit, it can shunt the reverse supply and causes a fuse or other current limiting circuit to open and thus protects the circuit.

6.4.3 Diodes in series and in parallel

Series

Diodes in series with V-I characteristics with same polarity, behave like a single diode. The voltage drop and current capabilities of each diode remains same. To increase power capability diodes are connected in series.

Parallel:

When load current is greater than the current rating of a single diode, then two or more diodes can be connected in parallel, to achieve a higher forward current rating. The fig shows the VI characteristics of two diodes. There is a different current flow in each diode. Total current flow is the sum of I_{D1} and I_{D2} . The total current rating is a value that can be just larger than the rating of one diode alone.

6.4.4 Different Types of diode

There are many types of diode, such as light emitting diodes, photo diodes, solar cell, tunnel diode etc.

- ◆ **Light emitting diodes:** For forward bias, electrons from n region cross the junction and goes to p region where it is neutralised with combination with holes. Some energy is released while going from higher energy state to lower energy state. For light emitting diode such energy is released as light. When the energy level difference falls in the range of some light energy, corresponding to frequency f , then that particular colour is emitted. In general LED's are of red, green, blue and yellow.

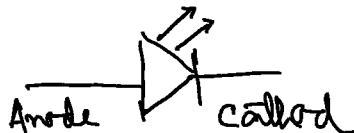


Fig 6.10a

- ◆ **Photo diode:** It is a junction diode which acts in the reversed bias region. Working of this diode depends on photoelectric effect. When $E_g = \hbar\omega$, then

photons of energy $\hbar\omega$ is absorbed in the diode and generates electron-hole pair at junction region and produces minority current.



Fig 6.10 b

- ◆ **Solar cell:** It is a special kind of photo diode; where solar energy is converted to electrical energy. Photons from Sun rays produce electron-hole pair and electrons flow towards n-region and holes towards p-region. When this cell is connected to a load, there is current through the load.

6.4.5 Rectifiers

Diodes are often used in power supply. It is an essential part of power supply and changes AC component to DC component of voltage or current. The unique property of a diode allowing current to flow in one direction is utilised in rectifier.

Half wave rectifier:

In half wave rectifier mains supply is applied at a primary of a step down transformer. As the positive half of the AC supply pass through the diode but the negative half cycles get eliminated. Peak value of output voltage is less than the peak value of input voltage due to the voltage drop across diode.

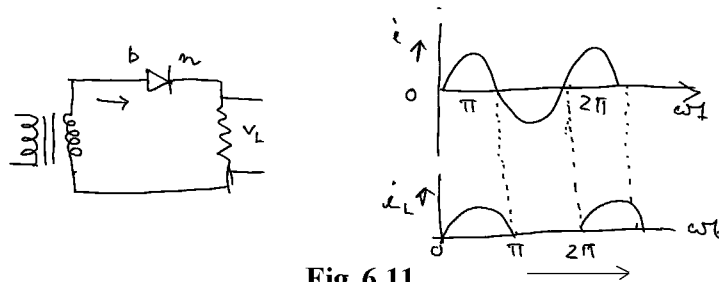


Fig 6.11

Ripple factor:

$$r = \frac{\text{rms value of ac component of load current(voltage)}}{\text{Mean value of load current(voltage)}} = \frac{I_{ac}}{I_{dc}}$$

$$= \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} \approx 1.21 \tag{6.4.3}$$

where, I_{rms} is the rms value of total load current and is given by

$$I_{rms}^2 = \frac{1}{2P} \int_0^{2P} i_L^2 d(\omega t) \quad 6.4.4$$

Full wave rectifier:

During the positive half of the transformer's secondary voltage, D_1 is forward biased and D_2 is reversed biased. So, current flows through D_1 and load R_L . During negative half cycle D_2 is forward biased and D_1 is reversed biased. In this case the current flows through, D_2 load R_L and lower half of the transformer winding. Thus, during both the half cycles the current flows through the load R_L in the same direction. There is a small voltage drop across the diode. So the peak value of the output voltage is less than the peak value of input voltage.

For full wave rectifier, load current flows in the same direction for both half of input voltage.

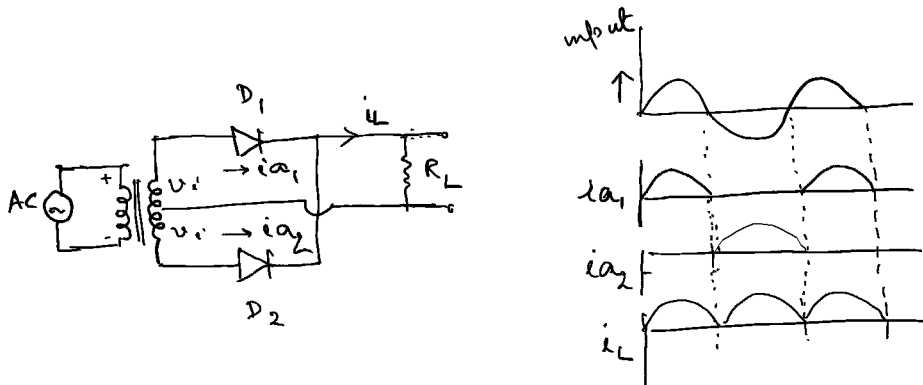


Fig. 6.12

Ripple factor:

$$r = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = 0.482 \quad 6.4.5$$

Bridge rectifier:

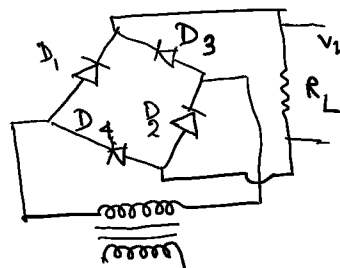


Fig 6.13

In bridge rectifier, during positive half cycle of the secondary voltage, diodes D_1 and D_2 are forward biased and D_3 and D_4 are reverse biased. Current will flow through secondary windings, D_1 , load R_L and D_2 . During negative half cycle D_3 and D_4 are forward biased and D_1 and D_2 are reverse-biased. Therefore current flows through secondary windings, D_3 , load R_L and D_4 . Hence current through the load is available for both half cycle of the voltage. Again peak value of the output voltage is less than the peak value of the input voltage by 1.2 volt.

Ripple factor is same as that of full wave rectifier.

Filter circuit:

The output of all rectifier circuit contains certain amount of ripples ie in addition to DC component there is AC component. To avoid such ripples filter circuit is used at the output of rectifier. There are two types of filter circuit; inductive and capacitive.

Capacitor input filter:

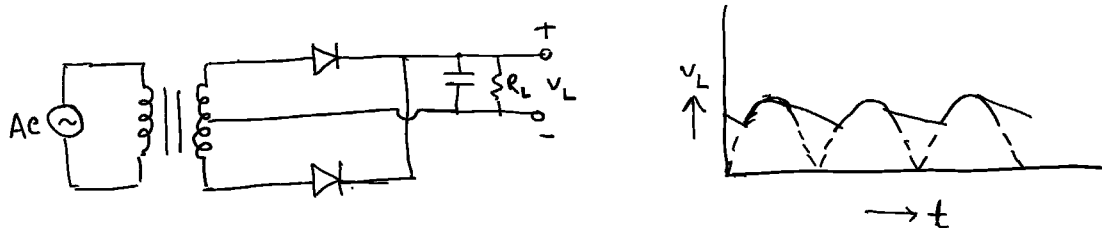


Fig 6.14

When a capacitor with high value capacitance is connected in parallel with the load R_L , the capacitor charges to peak voltage V_m during the half cycle output. After charging to the peak value, the capacitor discharges through the load resistor slowly. Before the capacitor voltage drops, next output cycle arrives and the capacitor recharges to the peak. In this way the ripple is reduced considerably.

6.5 Response of inductors and capacitors with DC or AC source

DC applied to inductors and capacitors:

In this chapter we shall study the transient response of electrical circuits excited by steady voltages. When an inductor or capacitor is connected to a source of steady

voltage, the current in the inductor or the charge on the capacitor does not attend the final steady value immediately. Similarly when the source is suddenly disconnected, the current in the inductor or the charge on the capacitor takes some time to attend the zero value. During the time interval between the switching operation and the final steady state of current or charging, the current and voltage in the circuit change with time. Such variation is known as transient in electrical circuits.

6.5.1 Growth and Decay of Current in Series LR Circuit

Suppose an inductor and a resistor is connected in series to a source of constant voltage V as shown in the fig 6.15a. When the switch is suddenly connected at time $t = 0$, the current in the circuit begins to grow. The magnetic flux linked with the inductor also increases and according to the Faraday's law of electromagnetic induction, a back emf $-L \frac{di}{dt}$ is generated in the circuit. This will oppose the driving emf V . If i be the instantaneous current generated in the circuit, the emf equation will be

$$V - L \frac{di}{dt} = iR \quad 6.5.1$$

$$\text{or, } L \frac{di}{dt} + iR = V,$$

$$\text{or, } \frac{di}{i - \frac{V}{R}} = \frac{R}{L} dt \quad 6.5.1a$$

At time $t = 0$, $I = 0$, so that

$$\int_0^i \frac{di}{i - \frac{V}{R}} = -\frac{R}{L} \int_0^t dt \quad 6.5.1b$$

$$\text{Or, } \ln \frac{i - \frac{V}{R}}{-\frac{V}{R}} = -\frac{Rt}{L}$$

$$\text{Or, } i = \frac{V}{R} \left(1 - e^{-\frac{R}{L}t} \right) = I_0 \left(1 - e^{-\frac{r}{L}t} \right) \quad 6.5.2$$

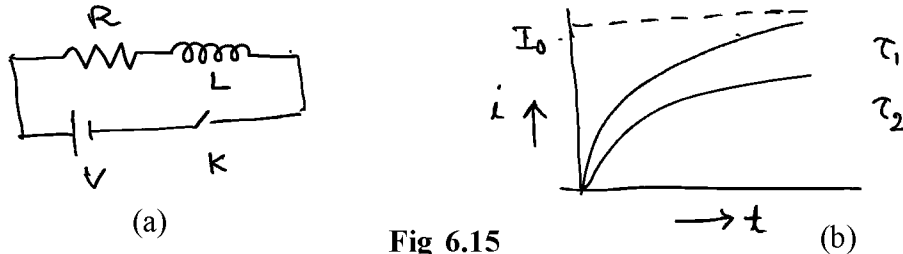


Fig 6.15

This is the equation for growth of current in a series LR circuit. Here, $i \rightarrow I_0$ the maximum steady current when $t \rightarrow \infty$. For all practical purposes the steady value is attained in a very short time. The quantity $\tau = \frac{L}{R}$ has the dimension of time and is known as the time constant of the circuit. At $t = \tau$, the current is

$$i = I_0(1 - e^{-1}) = .63I_0 \quad 6.5.2a$$

So the time constant is defined as the time in which the current in the circuit grows from zero to 63% of its final value. When L is large and R is small τ is large; this means it will take longer time to attend the steady state value. The instantaneous voltage and current across R and L are given by

$$V_R = iR = I_0 \left(1 - e^{-\frac{R}{L}t} \right) R \quad 6.5.3$$

And

$$V_L = L \frac{di}{dt} = RI_0 \left(e^{-\frac{R}{L}t} \right) \quad 6.5.4$$

Decay of Current:

When the steady current has been set up in the LR circuit, the switch is suddenly opened. The source is now cut off and the current in the circuit begins to fall. The emf equation will be

$$L \frac{di}{dt} + iR = 0 \quad 6.5.5$$

Or,
$$\frac{di}{i} = -\frac{R}{L} dt$$

At time $t = 0$, $i = I_0$, so that

$$\int_{I_0}^i \frac{di}{i} = -\frac{R}{L} \int_0^t dt \quad 6.5.5a$$

or,
$$\ln \frac{i}{I_0} = -\frac{R}{L} t$$

or,
$$i = I_0 e^{-\frac{R}{L} t} \quad 6.5.6$$

This is the equation for decay of current in a series LR circuit.

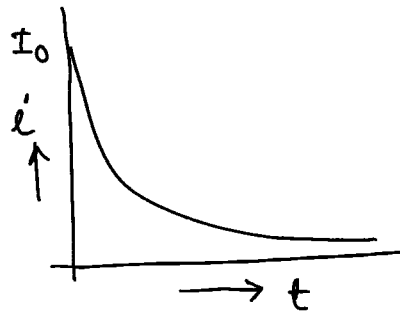


Fig 6.16

The rate of decay of current is given by

$$\frac{di}{dt} = -\frac{R}{L} I_0 e^{-\frac{R}{L} t} = -\frac{I_0}{\tau} e^{-\frac{t}{\tau}} \quad 6.5.7$$

The rate of decay also depends on the time constant. at $t = \tau$, $i = \frac{I_0}{e} = .37I_0$.

Thus the time constant may also be defined as the time in which the current decays to 37% of the initial value.

Instantaneous voltage drop across L and R:

$$V_L = L \frac{di}{dt} = -RI_0 e^{-\frac{R}{L} t} = -Ve^{-\frac{R}{L} t} \quad 6.5.8$$

$$V_R = RI_0 e^{-\frac{R}{L} t} = Ve^{-\frac{R}{L} t} \quad 6.5.9$$

It may be noted that during growth of current the source supplies energy, a part of which is lost as Joule heat in R and another part is used up to build magnetic

energy in L. During the break the magnetic energy stored in L is used up for driving current in the circuit.

6.5.2 Charging and discharging of a capacitor in DC circuit

A) Charging:

Let a DC voltage E is supplied across a circuit containing a capacitor C and a resistance R in series. When the circuit is switched on the capacitor will be charged by the voltage V . A part of the energy supplied by the source will be lost as Joule heat in R and the rest is used up for charging the capacitor.

Let q be the charge on the positive plate of the capacitor and i be the current at any instant of time t . So the instantaneous emf equation of the circuit is given by

$$\frac{E - \frac{q}{c}}{R} = i = \frac{dq}{dt} \quad 6.5.10$$

Or,
$$dt = \frac{Rdq}{E - \frac{q}{c}} = -CR \frac{d(E - \frac{q}{c})}{(E - \frac{q}{c})} \quad 6.5.11$$

At $t = 0$, $q = 0$, therefore

$$t = -CR \int_0^q \frac{d(E - \frac{q}{c})}{(E - \frac{q}{c})} = -CR \log \frac{(E - \frac{q}{c})}{E} \quad 6.5.12$$

Or,
$$q = EC(1 - e^{-\frac{t}{CR}}) \quad 6.5.13$$

At $t = \infty$, $q = q_0 = EC$

Therefore,
$$q = q_0(1 - e^{-\frac{t}{CR}}) \quad 6.5.7a$$

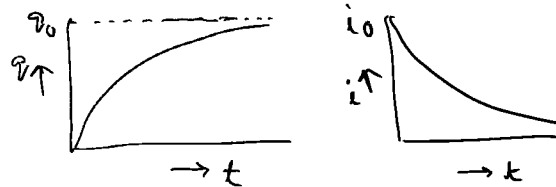


Fig 6.17

As before, $\tau = CR$ is known as the time constant of the circuit.

Rate of charging

$$\frac{dq}{dt} = \frac{q_0}{CR} e^{-\frac{t}{CR}}$$

At time $t=0$, $i = i_0 = \frac{E}{R}$

$$\therefore i = i_0 e^{-\frac{t}{\tau}} \quad 6.5.13$$

Discharging:

Let C is uniformly charged with charged with q_0 and then discharged through R. Then from equation 6.5.10, with $E = 0$,

$$i = -\frac{dq}{dt} = \frac{q}{R} \quad 6.5.15$$

or
$$\therefore CR \int_{q_0}^q \frac{dq}{q} = -\int_0^t dt, \text{ or} \quad 6.5.16$$

$$q = q_0 e^{-\frac{t}{\tau}} \quad 6.5.16a$$

The instantaneous current

$$i = \frac{dq}{dt} = i_0 e^{-t/\tau} \quad 6.5.17$$

Where $i_0 = -\frac{q_0}{CR}$

Eqn 6.5.16a and 6.5.17 are shown in the fig below.

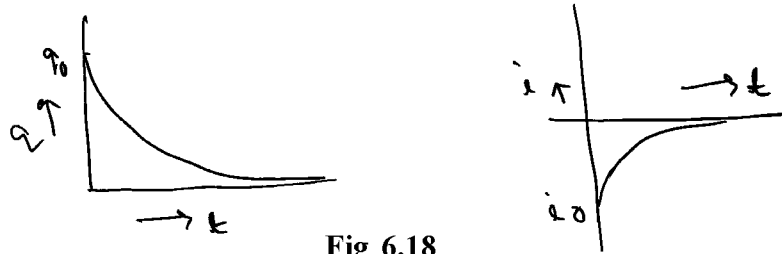


Fig 6.18

6.5.3 AC Source

Pure Inductors:

Let an alternating voltage $V = V_0 \sin \omega t$ be applied to the circuit containing pure inductance. L if i be the instantaneous current then the emf equation is

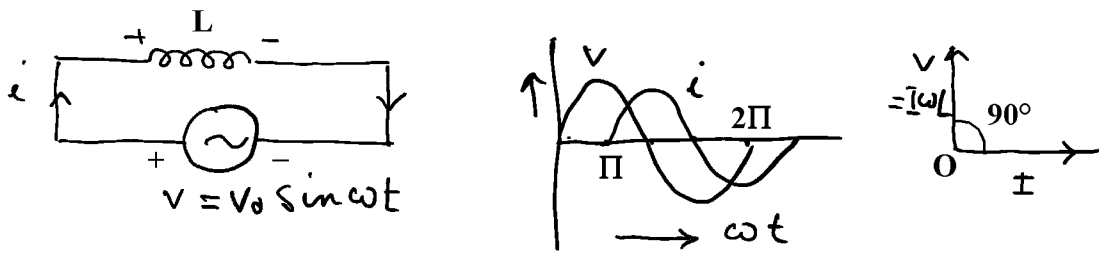


Fig 6.19

$$V = V_0 \sin \omega t = L \frac{di}{dt} \tag{6.5.18}$$

$$\text{or } \int_0^i di = \int_0^t \frac{V_0}{L} \sin \omega t dt \tag{6.5.18a}$$

$$\text{or } i = -\frac{V_0}{L\omega} \cos \omega t = -I_0 \cos \omega t = I_0 \sin(\omega t + \frac{\pi}{2}) \tag{6.5.19}$$

Here $\frac{V_0}{L\omega}$ is the peak current. $L\omega$ has the dimension of resistance and is known as inductive reactance. It is a measure of the opposition offered by L to the flow of AC through it. From equation 6.5.19 it is noted that the current i through a pure inductance lags behind the impressed AC voltage by 90° . So current attains a maximum value later than when V attains maximum. We know power dissipation is equal to $V \cos \phi$, ϕ is the phase lag. Since $\phi = 90$, $\cos \phi = 0$ and no power is dissipated. Thus a coil of high inductance and low resistance (negligible) offers a

high reactance to the flow of AC. It is useful to restrict current in an AC circuit. $L\omega$ increases with increase in frequency. As the frequency increases, more opposition to flow of current occurs. In this sense the inductor with high L is known as choke coil. This can be used to reduce current in AC circuit with no wastage of energy. If a resistance is used to reduce current, there is a dissipation of energy as Joule heat.

Pure Capacitor:

Let $V = V_0 \sin \omega t$ is applied across a capacitor C . The instantaneous charge on the capacitor C is

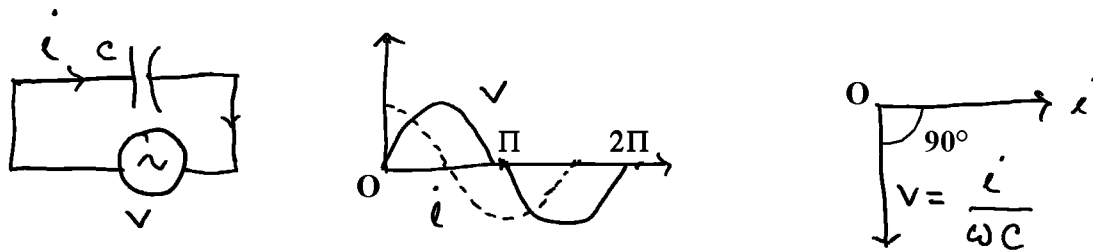


Fig 6.20

$$q = CV = CV_0 \sin \omega t. \quad 6.5.20$$

The instantaneous current is given by

$$i = \frac{dq}{dt} = \omega CV_0 \cos \omega t = \omega CV_0 \sin\left(\omega t + \frac{\pi}{2}\right), \quad 6.5.21$$

Where ωCV_0 or $\frac{V_0}{\frac{1}{\omega C}}$ is the peak current. $\frac{1}{\omega C}$ is called capacitive reactance and has the dimension of resistance. It is a measure of opposition offered by C to the flow of AC through it. The current i through a pure capacitor lead over the applied AC voltage by 90° . Here also $\cos \phi = 0$, leading to no power dissipation in pure C . $\frac{1}{\omega C}$ is small when C is large. So for large value of C . The capacitor can act as short circuit path for the AC through it, while it offers an infinite resistance to the flow of dc (as ω is zero). A large capacitor blocks dc component and allow ac to pass through it. Now $\frac{1}{\omega C}$ decreases with increase in the frequency of ac. In this case rate of charging increases with increasing t and hence reactance decreases.

The relation between current and voltage through inductance and capacitance and their phasor representations are shown in fig 6.19c and 6.20c respectively. Practical inductor may be represented as an inductance with a small series resistance and capacitor may be represented as a capacitor with a small series resistance.

Phasor:

Vectors which represent sinusoidal time varying quantities are known as phasors. Let j be an operator. When a given phasor A is along the x axis and is multiplied by the operator j a new phasor jA is obtained which will be 90° counter clockwise from A , i.e along Y axis.

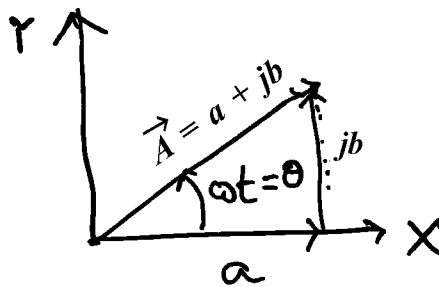


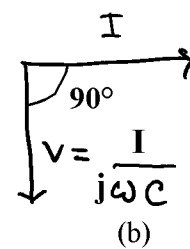
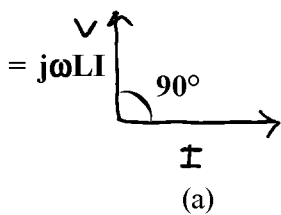
Fig 6.21

Then in Cartesian components, the vector $A = a + jb = Ae^{j\theta}$, $e^{j\theta}$ rotates the vector through an angle θ and $e^{-j\theta}$ rotates the vector through an angle $-\theta$. When $\theta = 90^\circ$, j is the operator which rotates the vector through 90° .

1. Since the voltage across the inductor leads the current passing through it by 90° , hence the inductive reactance ωL can be written as $X_L = j\omega L$.

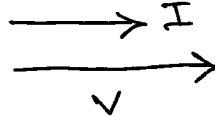
2. Since the voltage across the capacitor lags the current passing through it by 90° , hence the capacitive reactance $\frac{1}{\omega C}$ can be written as $X_C = -\frac{1}{\omega C} = \frac{1}{j\omega C}$.

The phasor diagram for pure inductive and capacitive circuit in applied AC voltage is shown in the fig below.



For pure resistance

$$V = V_0 \sin \omega t = iR \text{ or } i = \frac{V_0}{R} \sin \omega t = I \sin \omega t. \quad 6.5.22$$



Thus current and voltage are in same phase.

For practical inductor and capacitor (both has a resistance in series with them) voltage and current are not 90° out of phase but the phase angle is ϕ . For such inductive circuit, in terms of phasor,

$$I = \frac{V}{R + j\omega L} = \frac{V}{z},$$

where $R + j\omega L$ is known as complex impedance. R is real part or inphase part and $j\omega L$ is reactive part. Thus

$$I = \frac{V}{|z|} e^{j(\omega t - \phi)} \text{ or } \tan \phi = \frac{\omega L}{R} \text{ and } |Z| = \sqrt{R^2 + \omega^2 L^2}. \quad 6.5.23$$

For capacitive circuit,

$$I = \frac{V}{R + \frac{1}{j\omega C}} = \frac{V}{|z|} e^{j(\omega t + \phi)} \quad 6.5.24$$

$R + \frac{1}{j\omega C}$ is known as capacitive impedance and its magnitude is $\sqrt{R^2 + \frac{1}{\omega^2 C^2}}$.

L-R circuit

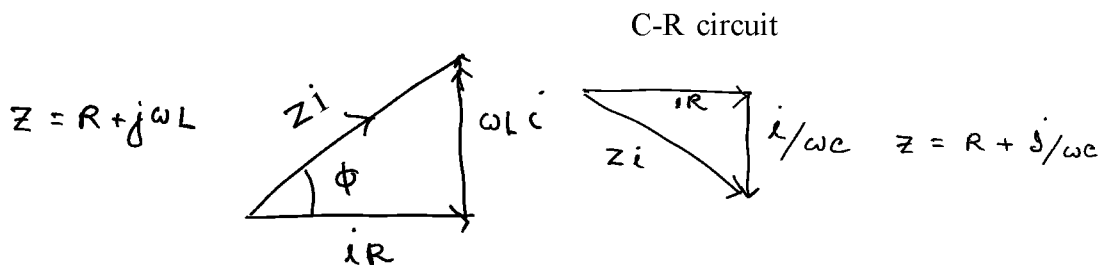


Fig. 6.22

6.6 Summary

Different combination of inductor, capacitor and resistors are used in different electrical circuit. In rectification process L type and Pi type filter is used. For rectification from AC to DC we need PN junction diode. Zener diode is used for voltage regulation.

6.7 Short questions

1. What are circuit elements? Define resistor, capacitor and inductor.
2. Two coils having self inductance L_1 and L_2 respectively are joined in a) series, b) parallel. If M be the mutual inductance between them, find effective self inductance.
3. Find the equivalent capacitance of two capacitors of capacitance C_1 and C_2 respectively when they are joined in a) series b) parallel.
4. What is a p-n junction? How is the depletion region formed in p-n junction?
5. State the principle of light emitting diode and photo diode.
6. What is a rectifier? Draw a neat circuit diagram for a) half wave b) full wave rectifier.
7. What is filter in rectifier circuit? Explain the action of C filter.
8. What is time constant in CR and in LR circuit? Show that the quantities CR and L/R have the same dimension of time.
9. A capacitor of $10\ \mu\text{F}$ is charged and then allowed to discharge through a resistor of $1\text{M}\ \Omega$. Find the time in which the charge on the capacitor reduces to 37% of its initial value. Ans 10s.
10. What is a phasor diagram? Draw phasor diagram for pure inductive and pure capacitive circuit in applied AC voltage. What will be the change in the phasor diagram for practical inductor and capacitor?

Unit 7 □ Electrical Protection

Structure

- 7.0 Objective**
- 7.1 Introduction**
- 7.2 Relays**
- 7.3 Fuses and disconnect switches**
- 7.4 Circuit breaker**
- 7.5 Overload devices**
- 7.6 Ground fault protection**
- 7.7 Grounding and isolating**
- 7.8 Phase reversal**
- 7.9 Surge protection**
- 7.10 Interfacing DC or AC sources to control elements (Relay protection devices)**
- 7.11 Summary**
- 7.12 Short questions**

7.0 Objective

In this chapter you gather knowledge on electrical protection

- Relay and its application
- Fuse and overload device
- Earthing and its necessity
- Surge Protection

7.1 Introduction

Protection of electrical circuits and appliances are essential. Ground fault detection and surge protection are required to maintain electrical equipment in good condition.

7.2 Relays

A relay is an electrically operating switch which works to isolate or change the state of an electric circuit from one state to another. Types of relays depend on the function for which they are used. Many relays use an electromagnet to operate mechanically a switch but other operating principles are also used, such as solid state relays. Solid state relays control power circuit using a semiconductor device to perform switching to protect electrical circuits from overload or faults.

Construction of electromagnetic relays and its operation:

It consists of a coil of wire wrapped around a soft iron core (a solenoid), an iron yoke which provides low reluctance path for magnetic flux. A movable iron armature consists of spring support or stand like structure connected to one end and a metal contact connected to other side. The armature is generally considered as a common terminal which is to be connected to the external circuitry. There are two pins namely normally opened (NO) and normally closed (NC). The NC pin is connected to the armature or the common terminal and the NO pin is left free (when the coil is not energised). When electric current is passed through the coil, it generates a magnetic field that activates the armature and gets connected to the normally opened contact till there exists flow of current through the coil. In such situation, external circuit connected to it functions in a different manner. When the current in the coil is switched off the armature is returned by a force to its relaxed position; the force is provided by the spring in general.

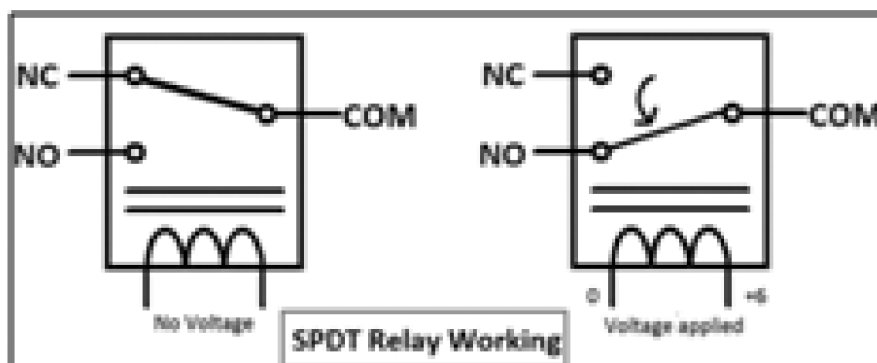


Fig. 7.1

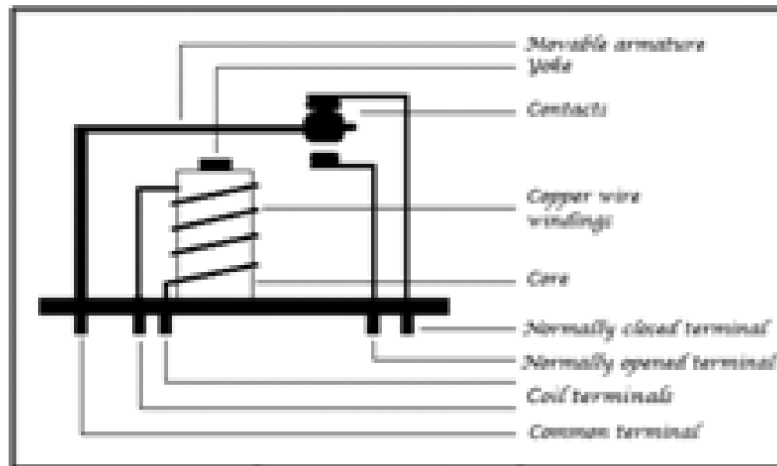


Fig. 7.2. An electromagnetic relay

Uses:

Apart from its use in large electrical circuit, relay is also used in a) computer circuit b) controlling the electrical motor switches, c) automated stabilisers, d) the circuit selection for more than one circuit in a system, e) television, f) traffic signal controllers, g) temperature controllers etc.

7.3 Fuses and disconnect switches

A fuse is an electrical safety device that operates to provide over current protection. It is an automatic means of removing power from a faulty system. It consists of a metal strip or wire of small cross section compared to the circuit conductors as fuse element. It is mounted between a pair of electrical terminals and usually enclosed by a non-combustible housing. The fuse is placed in series to the protected circuit, so that same current passes through it. Due to current flow heat is generated in the resistance. The size and construction of fuse element are so chosen that for normal current flow there is no appreciable rise in temperature. When large current flows the fuse element rises to a high temperature greater than the melting point of the fuse element and either melts directly or melts a soldered joint within the fuse, thus opening the circuit. Once a fuse has operated it is an open circuit and it must be replaced or rewired depending on the type.

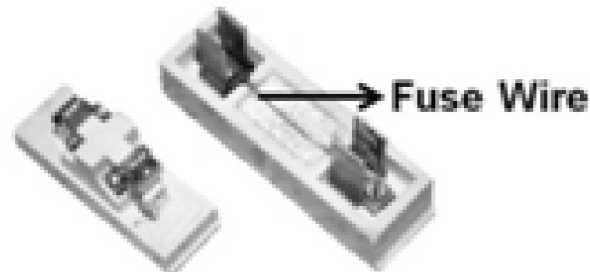


Fig. 7.3

The fuse element is made of zinc, copper, silver, aluminium or alloys. Nowadays there are thousands of fuse design each having specific voltage and current ratings, breaking capacity and response time depending on the application. A dual element fuse contains a metal strip that melts instantly on a short circuit and also contains a low melting solder joint which responds to long term overload of low values compared to a short circuit.

7.4 Circuit breaker

A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by excess current from an overload short circuit. When a fault is detected it will interrupt current flow in the circuit. Circuit breaker may be an alternative to fuse. Unlike a fuse, which operates once and must be replaced, a circuit breaker can be reset (either manually or automatically) to measure normal operation. CBs are categorised by the interrupting medium used. Minimum oil, air blast vacuum arc and SP6 CBs are some of the common examples. CB opens on relay command that initiates mechanical separation of the contacts. It has to handle large voltages(few hundreds of KV) and currents(in KA). The interrupting capacity of circuit breaker is expressed in MVA.



Fig. 7.4. Circuit breaker

Operation:

Power systems under fault behave like inductive circuit. The current in the inductive circuit cannot change instantaneously. The abrupt change in current if it happens due to opening of switch will induce infinite voltage or very high induced voltage. This high voltage developed across CB will ionise the dielectric between its terminals and results an arching. Usually CB opening time lies in the range 2-6 cycles. A CB opens on relay command that initiates mechanical separation of the contacts. When relay uses a trip command, it closes a switch that energises the CB opening mechanism powered by a separate dc source. The CB contact must carry the load current without excessive heating and must also withstand the heat of the arc produced when interrupting the circuit.

7.5 Overload devices

When the amount of current flowing through a circuit exceeds the rating of the protective devices, circuit overload occurs. Every electrical circuit in a wiring system must be protected against overload. There are two kinds of protection; a) the actual electrical wires associated with a circuit must be protected against the overload, b) individual appliances and electrical equipments connected to a circuit must be protected from overload. But types of protection involve fuses and circuit breakers.

Conductor protection:

Every electrical wire has a safe current rating. This is slightly different for different conductors, whether the conductors are used individually or in groups, the environment where the conductor is placed (open air, direct sun light, inside a building or in other situation). A fuse or CB is used to protect a particular wire from overloading must melt or trip before damage of the conductor or insulation is caused by the heating effect of the current flow to the conductor. If overload time is very short, the interrupting device may carry momentary overloads.

Equipment protection:

A fuse or CB is generally built into the appliances or electrical equipments to protect it from overload. The fuse or CB used to protect a wire is not useful enough to protect a device plugged on the current. When individual equipment fuses or

breakers are used, in addition to this, regular circuit protection fuse and CB are also needed. Thus while the fuse or CB protects the current against overload, the equipments are in safety protection by the individual equipment fuses or CBs and the whole system remains in safe.

7.6 Ground fault protection

Ground fault protection is equipment protection from the effect of ground faults. Ground fault occurs when electrical current finds an unintended path to ground. This is an unintended contact between an energised conductor and ground or equipment frame. The return path of the fault current is through the grounding system. Electrical faults are mainly in two categories; phase to phase and ground faults. Studies have shown that 98% of all electrical faults are ground faults. Phase to phase fault can be protected by using fuses and protective relays are required to protect against ground faults.

Causes of Ground fault:

The ground fault has its origin in different ways but the more common are reduced insulation, physical damages to insulation system or excessive transient or steady state voltage stresses on insulation. These problems are produced due to moisture, atmospheric contamination, insulation, mechanical stress etc.

Ground fault current magnitude can vary according to the grounding method used in the system. Although the ground fault current can reach values up to thousands of amps, the NEC in 2011 in the article 230.95(A) mentions that the maximum setting for ground fault protection must be 1200 Amps and maximum time delay must be 1sec for currents of 3000 amps or higher.

Ex. In the toaster circuit below the black or hot wire is shorted to the metal casing of the toaster. When the circuit is closed, part of current passes through the toaster frame and then the green ground wire. A protection relay could be installed to detect current as low as 5mA and will open the circuit breaker at a significantly lower level than the traditional circuit breaker does.

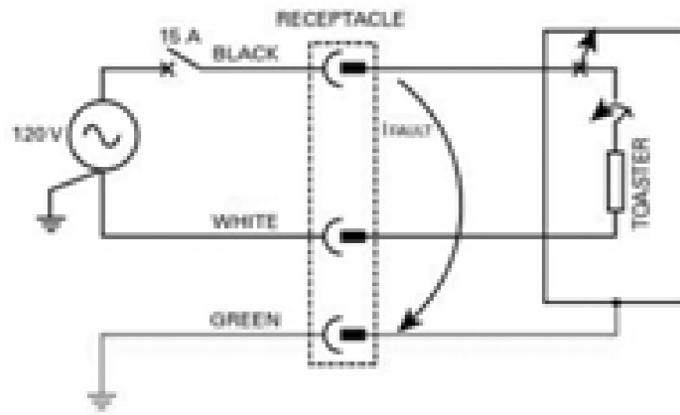
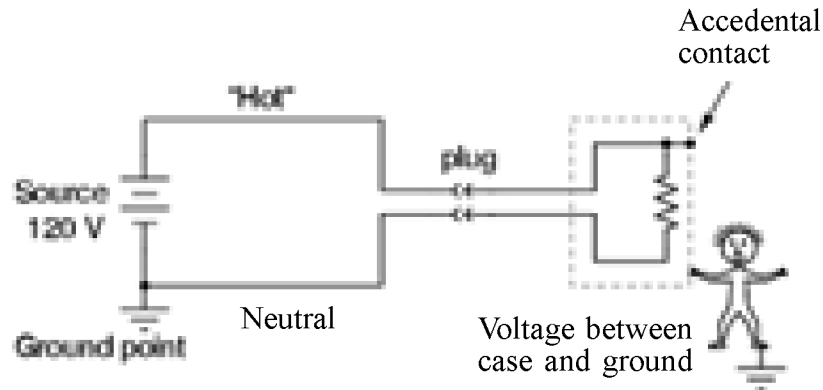


Fig. 7.5. Ground fault and toaster circuit

Action of ground fault relay:

In electrical circuit, current returns to its source. If some of the current is returning to the source through a different path (usually ground) the ground fault relay will detect this and if it exceeds a pre-determined amount for a predetermined amount of time, the ground fault relay will start operating.

For variable frequency drives, inverters, battery storage/UPS, a high quality ground fault relay is to be selected to remove harmonic frequencies and other noise from its measurements.

7.7 Grounding and isolating

Grounding is necessary for safety protection and performance reason. It is based on standards and no violation of safety rules can be done to improve the performance of the appliances or equipments. The metal part of equipments enclosures and racks which are susceptible to be energised by electrical currents must be grounded for personal safety reason and equipment protection.

The grounding is used to mean both equipment grounding and system grounding. Equipment grounding means the connection of earth ground to non-current carrying conductive materials such as conduit, cable trays, junction enclosures, motor frames. System grounding means the connection of earth ground to the neutral points of current carrying conductors such as the neutral point of a circuit, a transformer, rotating machinery either solidly or with a current limiting device.

There are mainly two different ways of grounding the electrical or electronic equipments. i) isolated ground and ii) standard ground. In the isolated grounding configuration, the metallic parts holding the load is directly connected to the general structure of the ground system. The standard ground configuration only needs a simple cable as ground conductor which is called protected earth.

Isolation:

Electrical isolation is basically a form of switching off an electrical circuit. Isolation is required to prevent damage to either electrical circuit when one of them is under fault condition. It is also done to isolate high voltage and low voltage circuit. Isolation refers to certain transformers where the primary winding is electrically isolated from the secondary winding. It is known as isolation transformer.

Transformers have the ability to convert between different levels of voltage and current in AC circuits. Apart from this, transformers has extremely useful features called isolation which is the ability to couple one circuit to another without the use of direct wire connections. There are appliances where electrical isolation is needed between two AC circuits without any transformation of voltage or current levels. Transformers that have a ratio of 1 to 1 between the primary and secondary windings are often used to protect secondary circuits and individuals from electrical shocks between energised conductors and earth ground. An isolation transformer is also

used to transfer electrical power from a source of AC power to some equipment or device while isolating the powered device from power source, for safety reason.

7.8 Phase reversal

Incorrect phase sequence within a three phase system is called phase reversal. Phase reversal occurs as a result of mistakes made during equipment installation, maintenance, or modification to the power system. When the phase sequence of a three phase system is incorrect, the connected three phase motors and other rotating equipment runs in the opposite direction. In many cases this may destroy product, damage machinery and injure personnel.

Phase Reversal Protection:

Phase Reversal Protection is used to protect the induction motor, from running in reverse direction. When the motor is empty (without mechanical coupling), running the motor in reverse direction does not affect the system. But with mechanical load, phase reversal causes heavy load current flow on the motors stator winding and severe damage on the mechanical side.

Phase reversal protection should be done in cranes lifts, or in belt conveyers, pump etc. A three phase monitor relay with a phase reversal protection should be used in appliances where three phase motors and other rotating equipment must not run in the reverse direction.

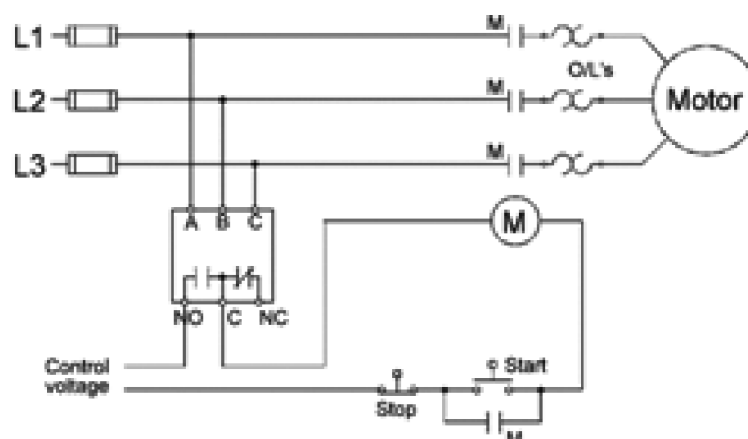


Fig. 7.6. Motor Phase Reversal Protection

Solid state relay sense the phase sequence of the motor. To install this relay, first we should run the motor without relay and find the correct direction of the motor. Then the phase reversal relay is to be installed. The relay will stop machinery if phase reversal occurs during operation.

7.9 Surge protection

In general, surge is a transient wave of current, voltage or power in an electrical circuit. Surges or transients are brief overvoltage spikes on a power waveform that can damage, degrade or destroy electronic equipments. Transients or surges can originate from inside (internal source) or outside (external source). **Internal source:** switching on off electrical loads, magnetic and inductive coupling, and static electricity. **External source:** mainly lightning can damage some of the more sensitive equipments.

A surge protection is an electrical device that is used to protect equipment against power surges and voltage spikes while blocking a voltage over a safe threshold (approximately 210 V). When a threshold is over 220 volt, a surge protector shorts to ground voltage or blocks the voltage. Though occasional power surges last only a fraction of a second yet without proper protection, electronic equipments or appliances would be damaged. Surge protection is a must to limit equipment damage and personnel injury.

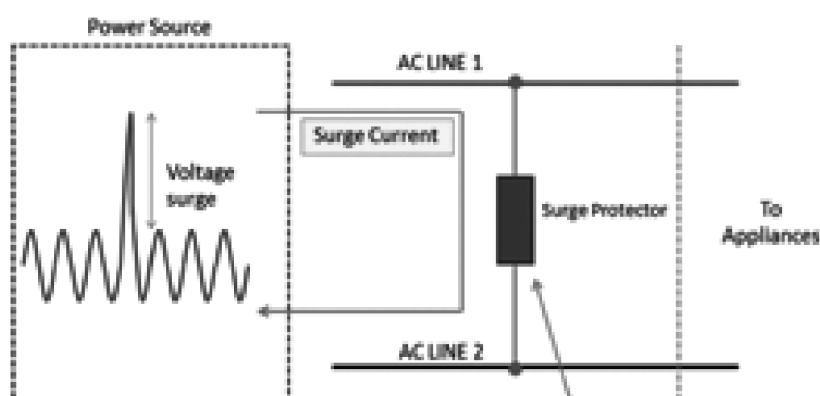


Fig. 7.7 Surge protection circuit

7.10 Interfacing DC or AC sources to control elements (Relay protection devices)

A protective relay is a device that detects the fault and initiates the operation of the circuit breaker (CB) to isolate the defective element from the rest of the system. The fault condition (one or more of the quantities, voltage, current, frequency and phase angle) are conveyed to protective relay through signal.

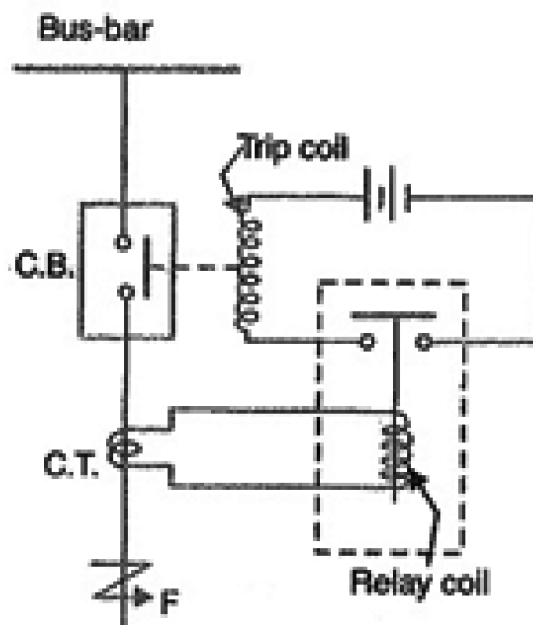


Fig. 7.8 Protective relay circuit

Protective relaying is used in electrical substations to give an alarm to cause prompt removal of any element of the power system from service when the element behaves abnormally.

Working:

When short circuit occurs at the point F on the transmission line, the current flowing in the line increases to a large value and as a result heavy current flows through the relay coil causing the relay to operate by closing its contacts. This closes the trip circuit of the breaker, making CB open and thus isolating the fault section from the rest of the system.

7.11 Summary

Relays are used to disconnect or reconnect from electrical contact from one point to another. It uses in stabilizer, computer, electrical motors etc. Fuses are one of the essential electrical circuit elements uses in every house and almost all electrical equipment. MCB is much more efficient electrical circuit breaker uses in nowadays. In order to protect from our house earthing is essential.

7.12 Short questions

1. Mention the protective devices used in electrical circuits.
2. Draw an electromagnetic relay circuit with proper labelling.
3. Explain briefly how an electrical fuse works.
4. What is a circuit breaker? What is its advantage over a switch?
5. What is meant by phase reversal? What is the effect of phase reversal on induction motor circuit?
6. When overload occurs in a circuit, how overload is protected in equipment?
7. What is ground fault and what is meant by ground fault protection?
8. Mention two methods for grounding electrical or electronic equipments.
9. What is surge in electrical circuit? What are the different sources of surge in electrical circuit; internal and external?
10. Explain how protective relay device works in a circuit?

Unit 8 □ Electrical wiring

Structure

8.0 Objective

8.1 Introduction

8.2 Different types of conductors and cables

8.2.1 Electrical Conductors

8.2.2 Wires and Cables

8.2.3 Electrical Cables:

8.3 Basic of wiring; star and delta connection

8.4 Voltage drop and losses across cables and conductors

8.5 Instruments to measure current, voltage, power in DC and AC circuit

8.5.1 Wattmeter

8.5.2 Power Measurement in Three Phase AC Circuits

8.6 Insulation

8.7 Solid and stranded cables

8.8 Summay

8.9 Short questions

8.0 Objective

In this chapter you gather knowledge on Electric wiring

- Electrical conductors and it type.
 - Electrical cables and its type.
 - Earthing and its necessity
 - Wattmeter
 - Electrical insulation
-

8.1 Introduction

Conductors are used to carry current. They are of different types and are in the form of wires. In electrical wiring in general a single wire is not used. Instead a group of wires known as cables are used. To protect electrical wires conduits

are used. Extension board is used in home or in laboratory purposes and hence the knowledge of preparation of extension board is required.

8.2 Different types of conductors and cables

8.2.1 Electrical Conductors:

Conductors are generally made up of metals like copper, aluminium and their alloys. It allows electrical current to flow through it. Generally electrical conductors are used in the form of wire. The conductor which is used in power transmission is usually stranded type which has great flexibility and mechanical strength as compared to a single wire of same cross-section area. In stranded conductor usually the entire wire is surrounded by the successive layers of wires containing 6, 12, 18, 24, .. wires. The equivalent cross-section of a stranded conductor is the area of cross-section of a solid conductor of the same material and length as the stranded conductor with same resistance at the same temperature.

Types of electrical conductor:

- I. **Hard drawn Copper conductor:** This type is most suitable for distribution work. It has high electrical conductivity, tensile strength, long life and high scrap value.
- II. **Cadmium Copper Conductor:** In this type the tensile strength of the copper is increased by 50% approximately by adding 0.7 to 1% cadmium at the cost of reduction of conductivity by about 15 to 17 %. The higher tensile strength enables the conductor to be used on longer spans, more resistance to atmospheric condition, and better resistance to wear and tear.
- III. **Steel Cored Copper Conductor (SCC):** Here one or two layers of copper strands surround a steel- cored copper conductor; the steel core adds the tensile strength of the conductor.
- IV. **Copper Welded conductor:** Uniform layers of copper are welded onto a steel wire, thus varying the conductivity to 30 to 60 percent to that of a solid copper conductor with same diameter. This type of conductors is used for longer span such as a river crossing.
- V. **Hard drawn Aluminium conductor:** Sometimes copper conductor is replaced by aluminium conductor due to reduced cost. The handling, transportation and erection of Al conductor become economical. It is used in the distribution lines in the urban area and short transmission line with lower voltage.

- VI. Aluminium Conductor Steel Reinforced (ACSR):** For the construction of long span lines, a steel core is added to the Al conductor. Such conductor is known as Steel Cored Aluminium Conductor (SCA) or ACSR. ACSR is light weight and has high tensile strength. In the specification 30Al/7St, It has seven steel strands forming a central core around which there are two layers of 30 aluminium strands.

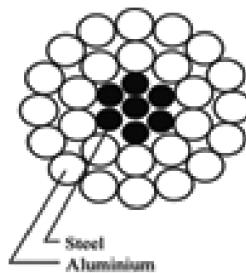
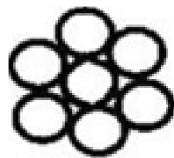
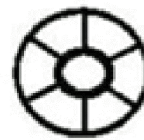


Fig. 8.2.1 ACSR conductor

- VII. Smooth Body ACSR conductor:** The conventional ACSR is pressed through dies to flatten the aluminium strands into segmental shape. The inter strand space is filled and the diameter of the conductor is reduced. This does not affect the electrical and mechanical properties. A conductor having ratio 6Al/1St is shown in the fig. below.



Conventional ACSR



Smooth body ACSR

Fig. 8.2.2

- VIII. Expanded ACSR Conductor:** In this case the diameter of conductor is expanded by filling fibrous or plastic material between the strands.

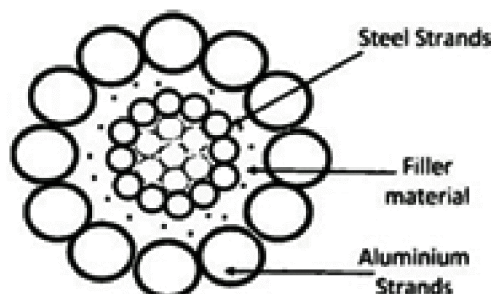


Fig. 8.2.3

- IX. All Aluminium alloy conductor:** These conductors are costly but have a good conductivity and tensile strength. The alloy containing 0.5% silicon, 0.5% magnesium and rest aluminium is used to make such conductor. These are mostly used in urban areas.
- X. ACAR Conductor:** Such conductor is similar to ACSR conductor but has a central core of alloys of aluminium surrounded by the layers of aluminium conductor. It has a better conductivity with the same strength weight ratio equal to that of ACSR with same diameter.
- XI. Alumo-weld Conductor:** In this case about 75% of a high strength steel wire is welded by aluminium powder. It is used in the cores of SCA conductor for making earth wire.
- XII. Phosphor Bronze Conductor:** This type of conductor is stronger than copper conductor but has a low conductivity. It is used for long span such as river crossing.
- XIII. Galvanized steel Conductor:** It has high tensile strength and is used in very long span and in rural area where load is small. It has a small life compared to other conductors.

8.2.2 Wires and Cables:

A wire is a single electrical conductor but a cable is a group of wires. Both wires and cables are used to carry electrical current. For smoothed electricity supply, wires and cables are to be carefully installed. For various electrical appliances, types of wires and cables to be installed are regulated by National Electrical Code (NEC) and local building code. For the correct choice, information is printed on wire covering regarding various features of electrical wire.

- 1. Size of wire:** The size of wire is determined by wire gauge. According to American wire gauge system, common wire sizes are 10, 12, 14.... Higher no. means a smaller wire size. The amount of power a wire can carry is determined by wire gauge. Higher is the gauge, smaller is the ampere requirement.
- 2. Wire Lettering:** According to NEC, the letters THHN, THWN, THW and XHHN represent the main insulation types of individual wires. Thus
T Thermoplastic Insulation

- H Heat resistance
- HH High Heat Resistance
- W Suitable for Wet location
- N Nylon Coating, resistance to damage by oil or gas
- X Synthetic Polymer flame resistant

3. Types of Wires:

Triplex Wires: It is composed of two insulated aluminium wires wrapped with a third bare wire used as a common neutral and of smaller gauge.

Main Feeder Wires: They are made of stranded or solid THHN wire. They are used to connect the service weather head to the house. They should be rated 25% more than the load required.

Panels Feed wires: They are generally black insulated THHN wires, used to power the main junction box and the circuit breaker panels. They should be rated for 25% more than the actual load.

Non Metallic Sheathed Wires: It consists of 2-3 conductors, each with plastic insulation, and a bare ground wire. The individual wires are covered with layer of non metallic sheathing. This type of wire is relatively cheaper, available in ratings of 15, 20, ... amps and is used in most homes.

Single strand wires: This type of wire is THHN wire type. In this case each wire is separated and multiple wires can be drawn together through a pipe cavity.

4. Colour Codes: Different colour codes are used for different purposes.

Black: Hot wire, for switches or outlets;

Red: Hot wire, for switch legs;

Blue and Yellow: Hot wires, pulled in conduit. Blue for 3-4 way switch application and yellow for switch legs to control fan, lights etc;

White: Always neutral;

Green and bare copper: For grounding.

5. Wire gauge, Amp and wattage: Wire gauge is the size of the wire, Amp is how much electricity can flow through the wire and wattage is the load a wire

can take and it is mentioned on appliances which is important for the choice of correct wire.

8.2.3 Electrical Cables:

Electrical cables are used to connect two or more devices to transfer electrical signals or power from one device to the other. Physically an electrical cable is an assembly of two or more conductors with their own insulations, individual coverings and protective coverings. Cables can be organised such as by using trucking, cable trays, cable lacing etc. Below is a list of different types of cables designed for applications from transmission to heavy industrial use.

- i. Coaxial cable:** A coaxial cable consists of a tubular insulating layer which protects an inner conductor which is surrounded by a tubular conducting shield and all are coaxial. This type is normally used for radio frequency signal for cable television distribution system.
- ii. Non metallic Sheathed Cable:** It consists of a flexible plastic jacket with two to four wires and a bare wire for grounding. They are also known as NMB and NMC non metallic sheathed cable and are mostly used for indoor residential purpose.
- iii. Underground Feeder Cable (UFC):** In this case instead of wrapping the individual wire in thermoplastic wire, the wires are grouped together and embedded in the flexible material. UF cables are highly water resistant and are used for outdoor lightning and in-ground application.
- iv. Metallic Sheathed Cable:** They are used to supply mains electricity or for large appliances. They consist of three plane stranded copper wires of which one wire for the current, one for grounding and one for neutral wire, and insulated with cross linked polyethylene, PVC bedding and a black PVC sheathing.
- v. Multi- conductor Cable:** Multi conductor or multi core cables consist of more than one conductor, each of which is insulated individually. Moreover, for extra security an outer insulation layer is added. This type of cable is simple to use and is used in home. A variant type like the audio multi core 'snake cable' is used in music industry.
- vi. Ribbon Cable:** Ribbon cable visualises like a flat ribbon. It is formed with various conducting wires parallel to each other on a flat plane. They are flexible, and are used in low voltage applications like computers and peripherals.

- vii. **Direct Buried Cable (DBC):** They are specially designed Coaxial or Bundled fibre-optic Cables to be buried under the ground without any kind of extra covering, sheathing or piping to protect it. They have specific tolerance to heat, moisture and other environmental factors and are used for transmission or communication purpose.
- viii. **Twin Lead Cable:** These are flat two- wire cable, used for transmission between an antenna and receiver, like TV.
- ix. **Twin Axial Cable:** This is similar to coaxial cable, having two inner conductors instead of one. It is used for very short range high speed signals.
- x. **Paired Cable:** It consists of two individual insulated conductors. It is normally used in DC or low freq. AC appliances.
- xi. ***Twisted Pair:** It is similar to paired cable, but the inner insulated wires are twisted or intertwined. Such cables are used in telephone lines for voice and data channels.
- xii. ***Unshielded Twisted Pair Cable (UTP):** This type consists of two wires twisted together. The individual wires are not insulated. This makes the cable perfect for signal transmission and video applications. UTP cables are often used in telephone, security cameras and data networks.

There are some other types of cables; such as communication cable, flexible cable, portable chord, shielded cable, single cable or wire, submersible cable.

Cable Colour Code:

Colour coding of cable insulation is done to determine active, neutral and earth conductors,. Different countries/region has different colour coding. The NEC has not prescribed any colour for phase/active conductors. However active conductors cannot be green, yellow, light blue or black.

Cable Size:

Cable size is determined by the gauge of individual wires within the cable, such as 14, 12, 10 etc; the bigger the number the smaller the size. The no. of wires in a wire-gauge is written like this; N/n, where n is the no. of wires of gauge N present in the cable.

8.3 Basic of wiring; star and delta connection:

In a three phase circuit, there are two types of connections; one type is known as star and the other type is known as delta connections.

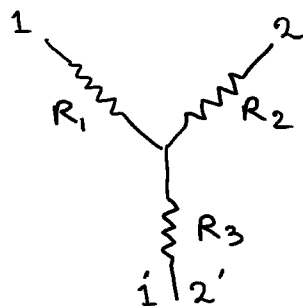
Star connection:

When the terminals of three branches are connected together to a common point to form a star like pattern, the network is known as star connection. The common point is known as star point or neutral point.

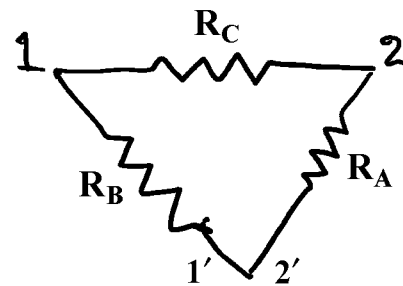
Delta connection:

In Delta connection, the end of each coil is connected to the starting point of the other coil that means the opposite terminals of the coils are connected together. In delta connection, there is no neutral point.

Star to Delta and Delta to Star conversion: In the analysis of complicated networks, sometimes it becomes convenient to replace a delta mesh by a star mesh and vice versa. This is known as star delta transformation.



Star connection (a)



Delta connection (b)

Fig. 8.3.1

Delta to Star conversion:

When resistances in the delta connection are given, the resistances in the star connection can be found out,

Let R_1 , R_2 and R_3 be the resistances in the star connection and R_A , R_B and R_C be the resistances in the Delta connection. Then from the figure 8.3.1(a) and (b).

The resistance between the terminal 11' is

$$R_{11'} = R_1 + R_3 = \frac{R_B(R_A + R_C)}{R_A + R_B + R_C} \quad 8.3.1$$

Similarly

$$R_{12} = R_1 + R_2 = \frac{R_C(R_A + R_B)}{R_A + R_B + R_C} \quad 8.3.2$$

$$R_{22'} = R_2 + R_3 = \frac{R_A(R_C + R_B)}{R_A + R_B + R_C} \quad 8.3.3$$

Adding we get

$$\therefore 2(R_1 + R_2 + R_3) = \frac{2(R_A R_B + R_B R_C + R_C R_A)}{R_A + R_B + R_C} \quad 8.3.4$$

From these equations we get

$$R_1 = \frac{R_B R_C}{R_A + R_B + R_C} \quad 8.3.5$$

$$R_2 = \frac{R_C R_A}{R_A + R_B + R_C} \quad 8.3.6$$

$$R_3 = \frac{R_A R_B}{R_A + R_B + R_C} \quad 8.3.7$$

Star to Delta conversion:

To convert star into its Delta equivalent, we note that

$$R_1 R_2 + R_2 R_3 + R_3 R_1 = \frac{R_A R_B R_C (R_A + R_B + R_C)}{(R_A + R_B + R_C)^2} = \frac{R_A R_B R_C}{(R_A + R_B + R_C)} \quad 8.3.8$$

Using equations 8.3.5, 8.3.6 and 8.3.7 we get

$$\text{Or, } R_A = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_1} \quad 8.3.9$$

$$R_B = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_2} \quad 8.3.10$$

$$R_C = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_3} \quad 8.3.11$$

When the resistances R_1 , R_2 and R_3 are replaced by the impedances Z_1 , Z_2 and Z_3 and resistances R_A , R_B and R_C are replaced by Z_A , Z_B and Z_C then from relation 8.3.5, 8.3.6 and 8.3.7, we get

$$Z_1 = \frac{Z_B Z_C}{Z_A + Z_B + Z_C} \quad 8.3.5a$$

$$Z_2 = \frac{Z_C Z_A}{Z_A + Z_B + Z_C} \quad 8.3.6a$$

$$Z_3 = \frac{Z_A Z_B}{Z_A + Z_B + Z_C} \quad 8.3.7a$$

Again from the relations 8.3.8, 8.3.9, 8.3.10 and 8.3.11, we may write,

$$Z_A = \frac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_1} \quad 8.3.9a$$

$$Z_B = \frac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_2} \quad 8.3.10a$$

and
$$Z_C = \frac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_3} \quad 8.3.11a$$

8.4 Voltage drop and losses across cables and conductors

In an electrical circuit when there is a decrease in voltage (or electrical potential) along the path of current in the circuit, it is called voltage drop. Voltage drop across cables and conductors are undesirable, because some of the supplied energy is dissipated within the cables and conductors. For efficiency of distribution and proper operation of electrical appliances, the national and local electrical codes have some guidance for the maximum voltage drop to be allowed in an electrical circuit. To maintain the voltage level accurately, there are techniques to compensate for the effect of voltage drop.

- i. To decrease the diameter of the wire between the source and the load so that overall resistance is increased.

- ii. A given amount of power can be transmitted with less voltage drop for power distribution system.
- iii. To use active elements to compensate for excessive voltage drop.

Note:

DC Circuit: The voltage drop in DC circuit is determined by Ohm's law and Kirchhoff's second law. Ohm's law states that voltage across a resistor is $V=IR$, where I is the current through the resistance R .

Kirchhoff's second law states that the sum of voltage drop across each component of the circuit is equal to the supply voltages.

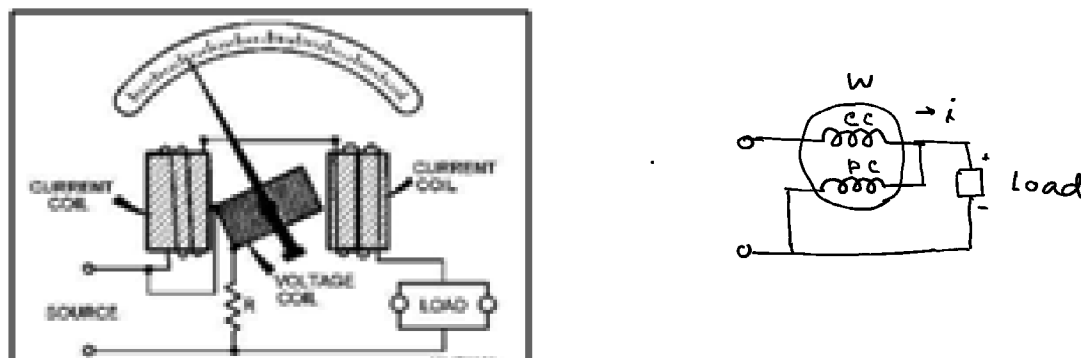
AC Circuit: For AC circuit, there is resistance as well as reactance (inductive or capacitive or both). So there is opposition to current flow due to impedance Z which is vector sum of resistance and reactance (capacitive or inductive). The voltage drop is given by $I|Z|$.

8.5 Instruments to measure current, voltage, power in DC and AC circuit

Multimeter can be used to measure both AC and DC current and voltages. Details of multimeter have been discussed in chapter 1.

8.5.1 Wattmeter

Wattmeter is used to measure electrical power. It consists of two coils; the current coil and the voltage coil. The current coil is connected in series with the circuit and the voltage coil is connected in parallel with the circuit. Current of the circuit passes through the current coil and the voltage is dropped across the voltage coil also named as potential coil. The potential coil is allowed to move whereas the current coil is kept fixed. The mechanical construction and the connection diagram of a wattmeter is shown in the figures below.



Electro-dynamometer wattmeter connection

Fig. 8.5.1

When the current passes through the current coil, it creates an electromagnetic field around the coil. The strength of this electromagnetic field is directly proportional to the amount of current passing through it.

In case of DC current, the current is also in phase with its generated electromagnetic field. The voltage is dropped across the voltage or potential coil and as a result, the needle moves across the scale. The needle deflection θ is proportional to the power W such that it is according to the product of the current passing and the voltage dropped, that is, Power $W = VI = k\theta$, k being a constant characteristics of the instrument. When V is in volt and I is in Amp, W is in watt.

AC Wattmeter

To measure AC power, dynamometer type of instrument is suitable for low frequency (< 1000 cps). As in DC circuit, the current coil is connected in series with the AC supply and a load while the voltage coil including a high non inductive resistance R , is in parallel with the supply (fig. 8.4.1). The mechanical couple between the two coils and hence the deflection of the moving coil is proportional to $E_{rms}I_{rms}\cos\phi$, where $\cos\phi$ is the power factor since the current and voltage are not in phase. The pointer attached to the coil can move over a scale which is directly calibrated in watts, which is the power dissipated in the load. (Power dissipated in the wattmeter itself is assumed to be negligibly small). The current through the voltage coil lags the emf by an angle $\theta = \tan^{-1} \frac{\omega L}{R}$. If $R \gg \omega L$, then $\theta \approx 0$ and the error is small.

Let the supply emf is represented by $e = E \sin \omega t$, and the load current is $i_l = I \sin (\omega t - \phi)$, The

$$\text{True voltage coil current is } i_c = \frac{E \sin(\omega t - \theta)}{\sqrt{R^2 + \omega^2 L^2}}$$

$$\begin{aligned} \text{Now } i_l i_c &= \frac{I \sin(\omega t - \phi) E \sin(\omega t - \theta)}{\sqrt{R^2 + \omega^2 L^2}} \\ &= \frac{EI}{\sqrt{R^2 + \omega^2 L^2}} [\sin^2 \omega t \cos \phi \cos \theta + \cos^2 \omega t \sin \phi] - \frac{\sin 2\omega t}{2} \sin(\theta + \phi). \end{aligned}$$

The mechanical couple between the coils is proportional to the mean value of $i_l i_c$ over a complete cycle. Thus the mean value over a cycle is

$$i_l i_c = \frac{EI \left(\frac{1}{2} \cos \phi \cos \theta + \frac{1}{2} \sin \phi \sin \theta \right)}{\sqrt{R^2 + \omega^2 L^2}} = \frac{EI \cos(\phi - \theta)}{2\sqrt{R^2 + \omega^2 L^2}}$$

$$\begin{aligned} \text{If inductance } L \text{ of voltage coil is zero then mean value of } i_l i_c &= \frac{EI \cos \phi}{2R} \\ &= \frac{E_{rms} I_{rms}}{R} \cos \phi. \end{aligned}$$

This is proportional to true power since R is small.

[Note: If apparent power be found by measuring r.m.s emf by AC voltmeter and r.m.s current by AC ammeter then power factor $\cos \phi$ can be obtained as the ratio of true power to the apparent power.]

Applications of Wattmeter

Wattmeter has extreme importance and extensive use in electrical measuring devices.

1. They are used in industries to check the power rating and consumption of electrical appliances.
2. Electromagnetic wattmeters are used to measure utility frequencies.
3. They are used with refrigerators, electric heaters and other equipment to measure their power ratings.

8.5.2 Power Measurement in Three Phase AC Circuits

Similar to the single phase AC power measurements, electro-dynamometer type of wattmeter is also used for three phase AC power measurements. Three phase power measurement can be applied for balanced or unbalanced load whether it is connected in either star or delta connection. The balanced load means the magnitudes of all impedances are equal, phase angles of all of them are equal and with same nature, either all resistive, or all inductive, or all capacitive. Otherwise the loads are said to be unbalanced.

8.6 Insulation

In electrical cables and equipments, insulating materials are used to separate electrical conductors without allowing current through themselves and this is called electrical insulations.

Materials like glass, paper, and teflon are good electrical insulators due to their high electrical resistivity. Some rubber like polymers and most plastics though may have lower resistivity, still are good as insulators and are used for insulation at normally used voltages for electrical wiring and cables. For high voltage systems containing transformers, liquid insulator oil is used to prevent arc. Overhead conductors for high voltage electrical power transmission are bare and are insulated by the surrounding air. For high voltage power transmission, insulating materials are made from glass, porcelain or composite polymer materials. Though glass has a higher dielectric strength than porcelain, yet it is difficult to cast irregular shapes without internal strain.

Types of insulators:

Though there are various types of insulators such as pin type insulator, post insulator, strain insulator, suspension insulator etc we discuss the suspension insulator.

Suspension insulator:

This type of insulators is generally used for voltage greater than 3.3 KV. It consists of number of glass or porcelain discs connected in series by metal links in the form of a string. The conductor is suspended at the bottom end of this string and the top end is secured to the cross arm of the tower. The number of disc units used depends on the voltage.

Insulation of electrical appliances:

All portable or hand held appliances are insulated to protect the users from harmful shock. There are two types of insulation.

- I. This requires that the metal body and other exposed metal parts of the appliances (device) be connected to earth via a grounding wire that is earth at the mains and needs only basic insulation on the conductors. So the appliance needs an extra pin on power plug for ground connection.
- II. Some appliances like hair drier, electrical shavers and some portable power tools, double insulation is required. This is sufficient to prevent electric shock. All internal electrically energised components are totally enclosed within an insulated body that prevents any contact with live parts. Double insulated appliances are marked with a symbol of two squares one inside other.

8.7 Solid and stranded cables

● Conduit:

An electrical conduit is a tube which is used to protect and route electrical wiring. Conduit may be rigid and also flexible type. Flexible conduit is used to connect to motors or other devices. PVC conduits are light in weight, lower in cost compared to other conduits. An assembly of conduit often known as duct bank may be installed between building- structures to allow installation of power and communication cables.



Fig. 8.7.1

● Cable trays:

It is an alternative to open wiring or electrical conduit system. They are useful for change of wiring system when new cables are installed by laying them in the tray instead of pulling them through a pipe or conduit.

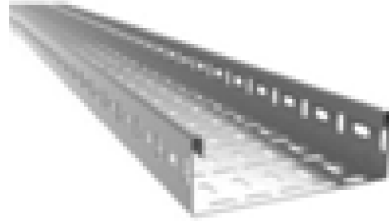


Fig. 8.7.2

- **Splices:**

Splicing is the process of combining two wires to carry current. There are many ways to splice wires together. It may be simply using wire caps or soldering wires together to carry current.

- **Wire nuts:**

The most common type of wire connectors are little plastic caps often called wire nuts. It twists over the bare end of the wires to make tight connections. The exterior part of them is made from insulating plastic materials. Inside it, there is a tapered coil metal insert which is used to thread onto the wires and hold them securely. This type of connection has the advantage that it can be unscrewed in future if we need to replace any device. Wire nuts are also known as twist on wire connectors used to fasten two or more low voltage electrical conductors. Wire nuts are used as alternative to terminal blocks or the soldering of conductors together. Wire nuts are available in a variety of sizes and shapes and they are commonly colour coded to indicate the connector size and hence their capacity.



Fig. 8.7.3

- **Crimps:**

An electrical crimp is a type of electrical connections. There are some advantages of crimping over soldering and wire nuts. i) Crimp may be designed to be gas tight to

prevent corrosion of metals due to oxygen. ii) Since no soldering alloy is used, the joint is mechanically stronger. iii) Crimp connections may be used for cables of both small and large cross sections but only small cross section wires are used with wire nuts.



Fig. 8.7.4

- **Terminal block:**

When there are a number of wires that need to be connected near each other or, if multiple outgoing wires are to be connected to a single incoming wire, then we use terminal blocks. A **terminal block** is a modular block with an insulated frame that secures two or more wires together. It consists of a clamping component and a conducting strip. A typical terminal block is as shown in the image below.

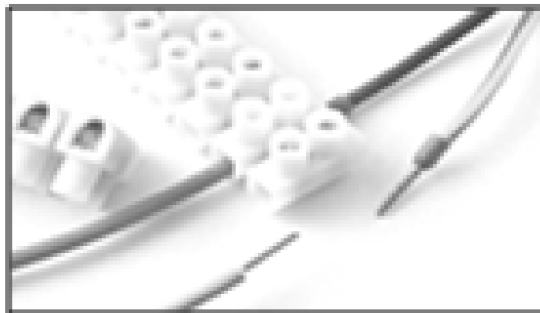


Fig. 8.7.5

The insulating body of a terminal block possess a current carrying element (a metal strip or terminal bar) and a base for clamping element. Terminal blocks keep connections much more secure and well organized.

To distribute power from a single input source to multiple outputs electric power distribution, terminal block is used. One large wire is connected to the input terminal of the block and multiple output terminals are provided at the output terminal

- **Split bolt:**

Split bolts are more commonly used to hold splices together. Two wires can be spliced into one by using a split bolt. The two ends of the wire are placed in the bolt, and the split is clamped down on the wires creating a connection. This is useful when working with wiring in large appliances, electronic devices, or home wiring.



Fig. 8.7.6

- **Solder:**

A soldering iron is a hand tool used in soldering. It is composed of a metal tip and an insulated iron. The metal tip is heated to melt solder material and can be applied into the joint between two work pieces. A fusible metal alloy used to create a permanent bond between metal work pieces. In order to adhere to and connect the pieces together the solder must be melted at first. The alloy suitable as solder material has a lower melting point than the pieces to be joined. For electrical and electronics work, solder wire is available in a range of thicknesses for manual soldering using a soldering iron. It is also available as a paste, as a pre-formed foil shaped to match the work pieces.



Fig. 8.7.7

Preparation of extension board

Extension board is used for many purposes for the extension of mains line. A correct knowledge about the wiring of the board is necessary. The preparation of the board is illustrated with figure.

The materials required for the preparation of the extension board are

- 1) Switch,
- 2) Plug,
- 3) Plug socket,
- 4) Extension cord,
- 5) Board with screws.

Step 1: Connection of wires to the plug:

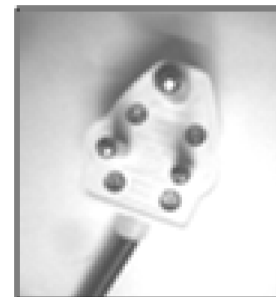
At first we shall connect the wires in the plug. There are three pin names on the plug: L, N and E (earthing). The plug is opened and three wires from a thick cord are taken out. We see three colour wires (R, B and G) in the cord. The wires are to be connected to the plug according to the colour code; red at L, black at N and green at E (fig 8.7.1a). Now wire the plug with L as Red wire, N as black wire and E as green wire (fig 8.7.1b). The bolts are now tightened and plug is covered to complete plug connection (fig 8.7.1c).



a



b



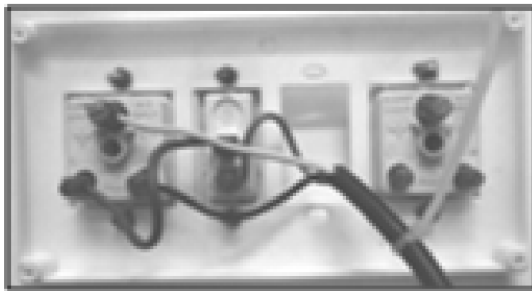
c

Fig. 8.7.8

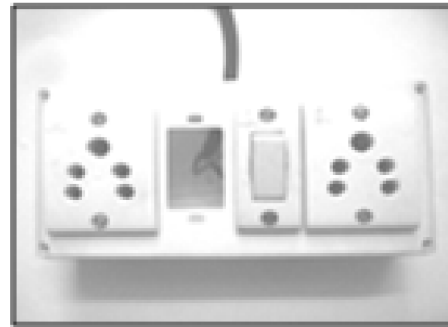
Step 2: Wiring of the board:

Now we have to wire the board with connection through one switch and plug socket. The board is opened to wire it. Pull out three coloured wire on the other side of the

chord. Connect a wire from switch to L of the plug socket and red end of the wire to the other connector of the switch. Now connect the black wire to the N pin of the plug socket and the green wire at the earthing terminal of the plug socket (fig 8.7.2a). Now the board is covered and the screws are tightened (fig 8.7.2b).



a



b

Fig. 8.7.9

The extension board is ready now (fig 8.7.2b) and can be used to power our home appliances.

8.8 Summary

Different kind of wire is used in electrical wiring. A bunch of wire covered by a non-conductor is used in general.

8.9 Short questions

1. How smooth body ACSR (Aluminium Conductor Steel Reinforced) is produced? Draw a picture of conventional ACSR and smooth body ACSR.
2. What is the difference between wire and cable? If wire sizes are 10, 12, 14...then which one means a smaller wires size. What is the use of cable colour code?
3. How cable size is determined? If n is the no. of wires of gauge N present in the cable, then how is it written on the cable?
4. What is the purpose of electrical insulation? Name two electrical insulating materials.

5. What is star connection and what is delta connection in an electrical circuit?
6. What are the different instruments used to measure current, voltage and power in ac and in dc circuits?
7. What is a wattmeter? Give a neat diagram of a wattmeter.
8. What is electrical conduit? Name two important electrical conduits.
9. How soldering is done by soldering iron?
10. What is the purpose of use of an extension board? Mention the materials required for the preparation of extension board?

Reference Book

1. Electricity & Magnetism — Murugesan
2. Electricity & Magnetism — Chattapadhyay & Rakhsit
3. Electricity & Magnetism — D. C. Tayal