Basics of Electrical & Electronics

Introduction

Introduction

Electric energy is convenient and efficient for production of light, mechanical energy and is also used in information processing. For the first two uses, it can be transported economically and in a clean fashion (as compared to transporting coal, for example) over long-distance lines to be available at the point of use.

Electric energy also can transport information over tremendous distances, with or without wires, equally efficiently and economically. There is almost no competitor to electric energy in these fields.

Electric energy does not occur naturally in usable form and must therefore be centrally generated and instantly transported to myriad points of use spread geographically over vast areas, even beyond state or national boundaries. It cannot be stored in large-enough quantities for any major use. Electric-energy generation is generally done through three processes:

1. Generating from naturally occurring chemically bonded energy as in fossil fuels (like coal and oil).
2. From nuclear energy, which is converted to heat form by combustion or nuclear fission. The thermodynamic cycle converts it to mechanical form (rotational) which is then employed to run an electric energy generator.
3. For limited use, electric energy is directly obtained from chemical energy, as in batteries, or solar energy is converted to electric energy as in a solar cell. The trend in electric energy generators is towards mega sizes, due to economy in large scales.

Introduction

Information, usually visual or audio signals or coded messages, have to be processed and/or transported by the intermediate form of electric energy. Speed of processing and the economy dictate that the electric energy for these purposes must be in minutest possible quantities, in either continuous form or bit form (modern trend). Hence, the trend is towards micro sizes. Range and variety of such use of electric energy is varied and wide as in video and audio systems, control processors, computers, etc.

Fibre optics using light signals is beginning to offer stiff competition to electric energy for purposes of information processing. The end-use energy form of such systems would, for a long time to come, continue to be electric.

This being the first chapter, it begins by introducing the fundamental laws of electricity and conservation of energy. The concepts of electric charge, current, voltage and electric sources and power are clarified along with the sign convention. Idealised circuit elements such as resistance, capacitance and inductance are dwelled upon along with basic laws that govern their terminal behaviour. The practical circuit elements such as resistor, capacitor and inductor are introduced.

Interconnection of circuit elements leads to the concept of electric circuit.

Introduction

The importance of circuit theory can be judged from the fact that almost all electric and electronic devices, transducers, transmission lines, energy and information processing systems, etc. are modelled in the form of a circuit with sources for the purpose of their analysis and design. Circuit modelling cannot be applied as such to very high-frequency devices (microwave equipment, etc.) where travelling-wave concept is necessary for their modelling.

In view of the above account, the electric circuit theory is fundamental to all fields of electrical engineering. An electric circuit on an analogic basis can model even some mechanical systems.

Syllabus Intro

Course Content	Weightage	Contact hours	Pedagogy
Unit 1: **Theory: Electrical Engineering** Study of voltage, current, power & energy. Application of Ohm's law, Kirchhoff's law, Lenz law. Electromagnetic induction through working of a transformer. **Practical:** Symbols of Electrical and Electronics equipment, Basics of Electrical safety & Study of Electrical Safety rules	20%	10	Chalk and Duster and PPT, Notes

Syllabus Intro

Unit 2: **Theory:** Concept of 1-phase, 3- phase AC supply. Introduction of terms like RMS value, average value. Familiarity with components like resistors, capacitors, diodes, LED's, their application, uses, industrial specification. Introduction to component data sheets.	25%	10	Chalk and Duster and PPT, Notes
Practical: Patch cords, Digital Multimeter (DMM), Familiarization with Digital multi-meter(DMM)			

Syllabus Intro

Unit 3: **Theory: Electrical Machines** Understanding the construction, type, principle of operation of various motors like DC, Stepper, Servo, AC. Introduction to the concepts of motor selection and sizing. **Practical:** Measurement of AC Voltage at 230 V AC Mains plug, Measurement of DC Voltage for cell phone battery of 3.8 V DC, Measurement of Resistance of Current coil & Potential coil of Energy meter, Measurement of Continuity of any wire/fuse.	25%	10	Chalk and Duster and PPT, Notes

Syllabus Intro

Unit 4: **Theory: Electronics Engineering** Introduction of electronic components like diodes, LED's, transistors, OpAmps, Gates Industrial specification and data sheets of the components. Characteristics and usage of the components. Signals: Analog & Digital. Introduction to industrial data acquisition **Practical:** Study the basics of 1-phase control transformer & verify its turn-ratio,Familiarization with Digital Storage Oscilloscope (DSO)	20%	10	Chalk and Duster and PPT, Notes

Syllabus Intro

Unit 5: **Theory: Test Equipment** Introduction to Multimeter and Oscilloscope **Practical:** Understand the construction & working of energy meter, Load Test on 1 Phase AC CSCR Type AC Motor, Load Test on DC Shunt Motor.	10%	5	Chalk and Duster and PPT, Notes

Syllabus Intro

<table>
<tr><th>Evaluation Scheme</th><th>Total Marks</th></tr>
<tr><td>Mid semester Marks</td><td>30</td></tr>
<tr><td>End Semester Marks</td><td>50</td></tr>
<tr><td>Continuous Evaluation Marks</td><td><table>
<tr><td>Attendance</td><td>5 marks</td></tr>
<tr><td>Quiz</td><td>5 marks</td></tr>
<tr><td>Skill enhancement activities / case study</td><td>5 marks</td></tr>
<tr><td>Presentation/ miscellaneous activities</td><td>5 marks</td></tr>
</table></td></tr>
</table>

Syllabus Intro

Learning Resources	
1.	Textbooks:1.Albert Paul Malvino," Electronic Principles", Tata Mcgraw Hill,2002
2.	Reference Books: 1.Simon Haykin, "Communication Systems", Wiley Eastern, Third Edition,19
3.	Journals & Periodicals:
5.	Other Electronic Resources:

Introduction

ELECTRICITY

The invisible energy that constitutes the flow of electrons in a closed circuit to do work is called 'electricity'.

It is a form of energy that can be easily converted to any other form. Previously, it was thought that electricity is a matter which flows through the circuit to do work. However, now it has been established that electricity constitutes the flow of electrons in the circuit, and in this process, a work is done. It can be well explained by 'Modern Electron Theory'.

MODERN ELECTRON THEORY

The following conclusions were drawn

1. Every mater is electrical in nature since it contains the charged particles such as electrons and protons.
2. Under ordinary conditions, a body is electrically neutral since every atom of the body material is having the same number of protons and electrons.
3. Each matter differs from the other since they have different atomic number and structure.
4. An atom cannot have more than one free electron at the same instant. For example, in case of aluminium, there are three electrons in the outermost (third) orbit but only one of them is free at a time.

Introduction

5. Silver is more conductive material than the other two (i.e., copper and aluminium), since in case of silver atomic structure, the free electron is in the fifth orbit and is more loosely attached. However, copper is more conductive than aluminium since the free electron in case of copper atomic structure is in the fourth orbit. The aluminium is the poorest conducting material of the three, since in its atomic structure the free electron is in the third orbit and is more rigidly attached to the nucleus.

NATURE OF ELECTRICITY

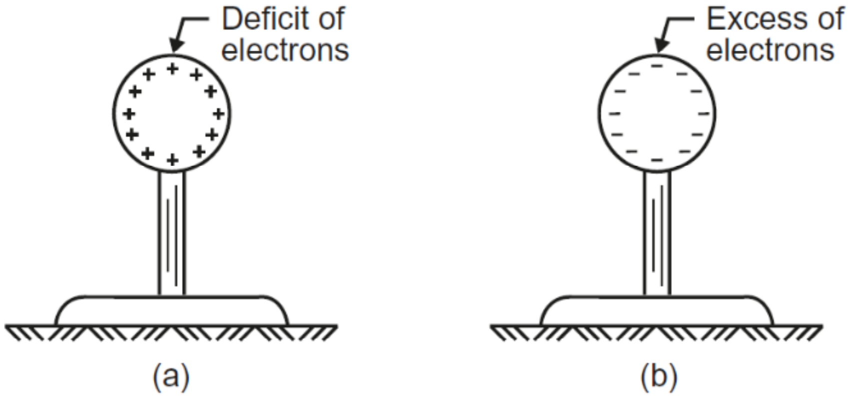
It has been observed that every matter is electrical in nature, since it contains charged particles such as protons and electrons. Therefore, the following points are observed:

1. A body is neutral as it contains same number of protons and electrons.
2. If some of the electrons are removed from the body,[1] then a deficit of electrons occurs, and the body attains a positive charge.
3. If some of the electrons are supplied to the body, then the number of electrons will be more, and the body attains a negative charge.

Introduction

CHARGED BODY

Every substance or body is electricity neutral as all the atoms of the body contain equal number of electrons and protons.



Charged bodies (a) Positively charged body (b) Negatively charged body

However, when some electrons are detached from the body, a deficit of electrons occurs. As a result, the body attains positive charge [Fig. 1.2(a)], whereas if the electrons are supplied to a neutral body, then the number of electrons will be more than its normal due share. Hence, the body attains negative charge [Fig. 1.2(b)]. Therefore, a body is said to be charged positive or negative if it has deficit or excess of electrons from its normal due share, respectively.

Introduction

UNIT OF CHARGE

The charge on an electron is very small, and it is not convenient to take it as the unit of charge. Therefore, coulomb[2] is used as the unit of charge in practice. Hence, the practical unit of charge is coulomb.

$$1 \text{ coulomb} = \text{charge on } 628 \times 10^{16} \text{ electrons}$$

If a body is said to have a negative charge of one coulomb, then it means that the body has an excess of 628×10^{16} electrons from its normal due share.

FREE ELECTRONS

The valance electrons that are very loosely attached to the nucleus of an atom and can be easily detached are called free electrons. These free electrons are so loosely attached to the nucleus that they do not know the atom to which they belong originally. Thus, they move from one atom to the other at random in the metal itself. It has been observed that in the metals, all the valence electrons are not the free electrons at a time. In fact, one atom can provide only one free electron at a time. However, a small piece of metal has similar number of atoms and free electrons (i.e., billions of atoms and free electrons).

Introduction

ELECTRIC POTENTIAL

The capacity of a charged body to do work is called electric potential. Obviously, the measure of electric potential is the work done to charge a body to one coulomb, that is,

$$\text{Electric potential} = \frac{\text{Workdone}}{\text{Charge}} \quad \text{or} \quad V = \frac{W}{Q}$$

Unit: Since work done is measured in joule and charge in coulomb, the unit of electric potential is joule/coulomb or volt.

POTENTIAL DIFFERENCE

The difference in the electric potential of the two charged bodies is called potential difference.

Unit: The unit of potential difference is volt.

Introduction

ELECTRIC CURRENT

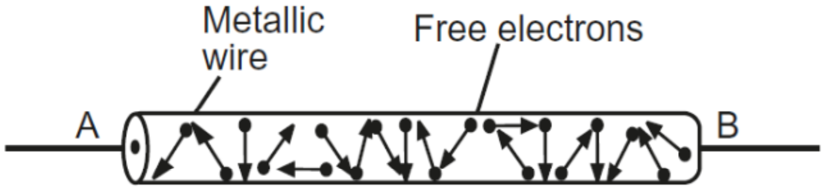


Fig. 1.3 Random movement of free electrons in metals

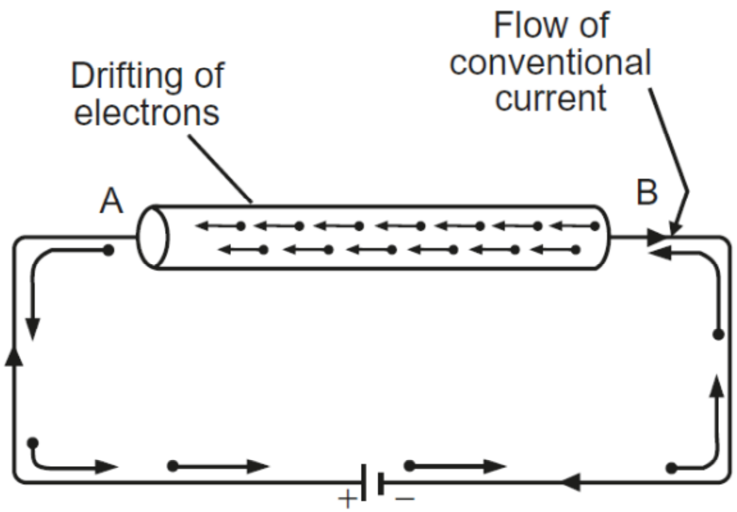


Fig. 1.4 Continuous drifting of free electrons constituting electric current

When an electric potential difference is applied across the metallic wire, the loosely attached free electrons, as shown in Figure 1.3, start drifting towards the positive terminal of the cell (see Fig. 1.4). This continuous drifting of electrons constitutes the electric current. Therefore, a continuous drifting of electrons in an electric circuit is called electric current.

The drifting of electrons in the wire is from B to A, that is, from negative terminal of the cell to the positive terminal through external circuit.

Introduction

Conventional Direction of Flow of Current

Prior to electron theory, it was believed that some matter flows through the circuit when a potential difference is applied, which constitutes electric current.

It was considered that this matter flows from higher potential to lower potential, that is, positive terminal to negative terminal of the cell through external circuit.

This convention flow of current is so firmly established that it is still in use. Therefore, the conventional direction of flow of current is from A to B, that is, from positive terminal of the cell to the negative terminal through the external circuit.

The magnitude of flow of current at any section of the conductor is the rate of flow of electrons, that is, charge flowing per second. It can be expressed mathematically as follows:

Current, $$I = \frac{Q}{t}$$

Unit: Since charge is measured in coulomb and time in second, the unit of electric current is coulomb/second (C/s) or ampere (A).

Introduction

RESISTANCE

The opposition offered to the flow of electric current or free electrons, as shown in Figure 1.5, is called resistance.

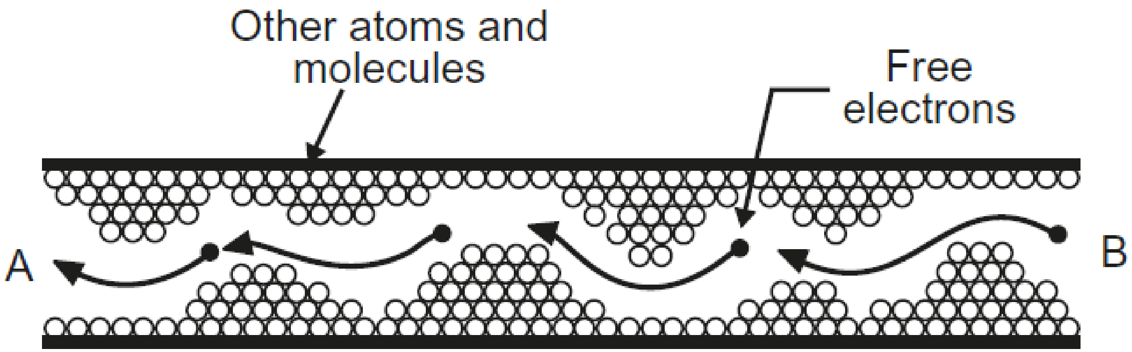


Fig. 1.5 Opposition offered to electric current

Unit: Resistance is measured in ohm (or kilo ohm) and is denoted by symbol Ω or kΩ.

A wire is said to have a resistance of one ohm if one ampere current passing through it produces a heat of 0.24 calorie (or one joule).

Introduction

Laws of Resistance

The resistance (R) of a wire depends upon the following factors:

1. It is directly proportional to its length, l, that is, $R \propto l$.
2. It is inversely proportional to its area of cross section, a, that is,

$$R \propto \frac{1}{a}$$

3. It depends upon the nature (i.e., atomic structure) of the material of which the wire is made.
4. It also depends upon the temperature of the wire.

Neglecting the last factor for the time being $R \propto \frac{1}{a}$ or $R = \rho \frac{1}{a}$

where ρ ('Rho' a Greek letter) is a constant of proportionality called resistivity of the wire material. Its value depends upon the nature (i.e., atomic structure) of the wire material representing the third factor earlier.

Introduction

RESISTIVITY

The resistivity of a wire is given by the relation: $R = \rho \frac{1}{a}$

If $l = 1$ m and $a = 1$ m^2 (Fig. 1.6(a)), then $R = \rho$

Hence, the resistance offered by one-metre length of wire of given material having an area of cross-section of one square metre is called the resistivity of the wire material.

In place of wire, if a cube of one metre side of a given material is taken as shown in Figure 1.6(b), then consider opposite two faces of the cube.

$$l = 1 \text{ m};\ a = 1 \times 1 = 1 \text{ m}^2 \text{ and } R = \rho$$

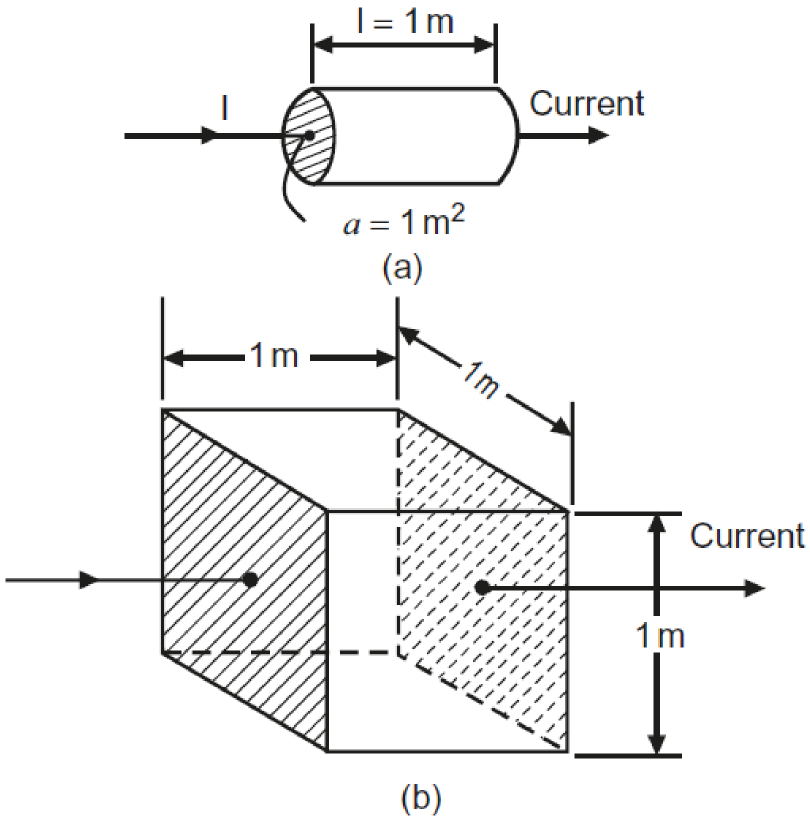


Fig. 1.6 Conductor size to determine specific resistance (a) Wire (b) Cube of 1 m side

Introduction

RESISTIVITY

Hence, the resistance offered between the opposite two faces of one-metre cube of the given material is called the resistivity of that material.

Unit: We know that $R = \rho \frac{l}{a}$ or $\rho = \frac{Ra}{l}$

Substituting the units of various quantities as per SI units, we get

$$\rho = \frac{\Omega \times \mathrm{m}^2}{\mathrm{m}} = \Omega - \mathrm{m}$$

Hence, the unit of resistivity is ohm metre in SI units.

SPECIFIC RESISTANCE

Specific resistance of a material is defined as the resistance of the material having specific dimensions, that is, one-metre length and one square metre as area of cross-section.

Introduction

CONDUCTANCE

The ease to the flow of current is called conductance. It is generally denoted by letter G.

We know that the opposition to the flow of current is called resistance. Hence, conductance is just reciprocal of resistance, that is,

$$G = \frac{1}{R} = \frac{1 \times a}{\rho\, l} = \sigma \frac{a}{l}$$

Unit: The unit of conductance is mho (i.e., ohm spelt backward). The symbol for its unit is ℧.

Conductivity

From the expression given earlier, σ ('Sigma' a Greek letter) is called the conductivity or specific conductance of the material. It is basically the property or nature (i.e., atomic structure) of the material due to which it allows the current to flow (conduct) through it.

$$G = \sigma \frac{a}{l} \quad \text{or} \quad \sigma = G \frac{l}{a}$$

Substituting the units of various quantities, we get

$$\sigma = \frac{\mho \times \mathrm{m}}{\mathrm{m}^2} = \mho/\mathrm{m}$$

Hence, the unit of conductivity in SI units is mho/metre.

Introduction

ELECTROMOTIVE FORCE

The electromotive force (emf) of a source, for example, a battery, is a measure of the energy that it gives to each coulomb of charge. Initially, emf implies that it is a force that causes the electrons (the charged particles, i.e., current) to flow through the circuit. In fact, it is not a force but it is an energy supplied by some active source such as battery to one coulomb of charge.

Introduction

EMF AND POTENTIAL DIFFERENCE

The amount of energy supplied by the source to each coulomb of charge is known as emf of the source, whereas the amount of energy used by one coulomb of charge in moving from one point to the other is known as potential difference between the two points.

For instant, consider a circuit as shown in Figure 1.7. If a battery has an emf of 12 V, it means that the battery supplies 12 joule of energy to each coulomb of charge continuously. When each coulomb of charge travels from positive terminal to negative terminal through external circuit, it gives up whole of the energy originally supplied by the battery.

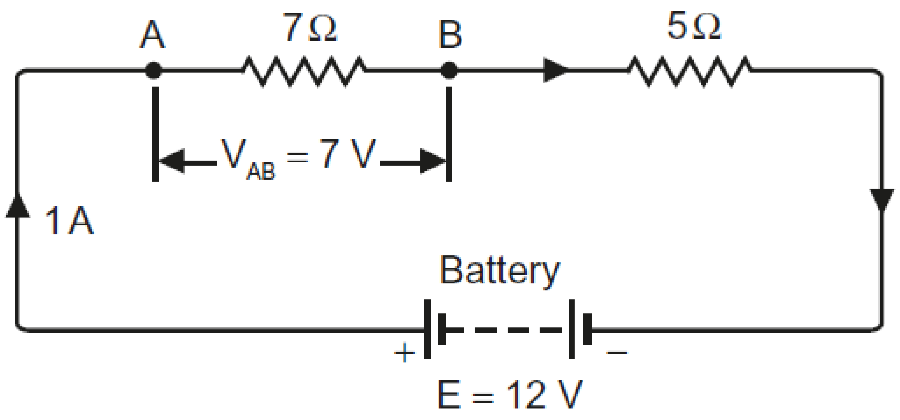


Fig. 1.7 Electric circuit to represent emf and potential difference

The potential difference between any two points, say A and B, is the energy used by one coulomb of charge in moving from one point (A) to the other (B). Therefore, potential difference between points A and B is 7 V.

Ohm's Law

OHM'S LAW

Ohm's law states that the current flowing between any two points of a conductor (or circuit) is directly proportional to the potential difference across them, as shown in Figure 1.8, provided physical conditions i.e. temperature etc. do not change.

Mathematically $I \propto V$

or $$\frac{V}{I} = \text{constant} \quad \text{or} \quad \frac{V_1}{I_1} = \frac{V_2}{I_2} = \cdots = \frac{V_n}{I_n} = \text{constant}$$

In other words, Ohm's law can also be stated as follows:

The ratio of potential difference across any two points of a conductor to the current flowing between them is always constant, provided the physical conditions, that is, temperature, etc., do not change.

This constant is called the resistance (R) of the conductor (or circuit).

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

It can also be written as $V = IR$ and $I = \dfrac{V}{R}$.

In a circuit, when current flows through a resistor, the potential difference across the resistor is known as voltage drop across it, that is, $V = IR$.

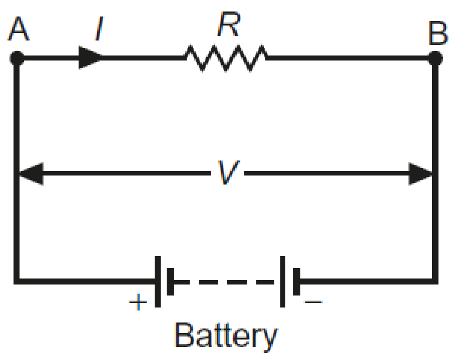


Fig. 1.8 Potential difference (voltage) applied across a wire having resistance R ohm

Ohm’s Law

Limitations of Ohm’s Law

Ohm’s law cannot be applied to the non-linear clients such as circuits containing electronic tubes or transistors and the circuits used to produce electric arc.

Example

A current of 0.75 A is passed through a coil of nichrome wire which has a cross sectional area of 0.01 cm^2. If the resistivity of the nichrome is 108×10^{-6} ohm cm and the potential difference across the ends of the coil is 81 V. What is the length of the wire? What is the conductivity and conductance of the wire?

Solution:

Resistance, $$R = \rho\frac{1}{a}$$

$$R = \frac{V}{I} = \frac{81}{0.75} = 108\ \Omega;\ a = 0.01\,\text{cm}^2 = 0.01\times10^{-4}\,\text{m}^2$$

Where $$\rho = 108\times10^{-6}\,\Omega\ \text{cm} = 108\times10^{-8}\,\Omega\ \text{m}$$

$\therefore$ $$l = \frac{V}{I} = \frac{Ra}{\rho} = \frac{108\times0.01\times10^{-4}}{108\times10^{-8}} = 100\ \text{m (Ans.)}$$

Ohm's Law

Conductivity, $$\sigma = \frac{1}{\rho} = \frac{1}{108 \times 10^{-8}} = 92.59 \times 10^{4} \text{ mho/m (Ans.)}$$

Conductance, $$G = \frac{1}{R} = \frac{1}{108} = 9.259 \times 10^{-3} \text{ mho (Ans.)}$$

EFFECT OF TEMPERATURE ON RESISTANCE

The electrical resistance generally changes with the change of temperature. The resistance does not only increase with the rise in temperature but it also decreases in some cases. In fact, the increase or decrease in resistance with the rise in temperature depends on the nature of the resistance material discussed as follows:

1. **Pure metals:** When the resistance is made of some pure metal (copper, aluminium, silver, etc.), its resistance increases with the increase in temperature. The increase is large and fairly uniform for normal range of temperature, and therefore, temperature–resistance graph is a straight line. Thus, pure metals have positive temperature coefficient of resistance.

Work / Energy / Power

2. **Alloys:** When the resistance is made of some alloy (e.g., Eureka, Manganin, Constantan, etc.), its resistance increases with the increase in temperature. But the increase is very small and irregular. In the case of above-mentioned alloys, the increase in resistance is almost negligible over a considerable range of temperature.
3. **Semiconductors, insulators, and electrolytes:** The resistance of semiconductors, insulators, and electrolytes (silicon, glass, varnish, etc.) decreases with the increase in temperature. The decrease is non-uniform. Thus, these materials have negative temperature co-efficient of resistance.

ELECTRICAL ENERGY

When a potential difference V (volt) is applied across a circuit, as shown in Figure 1.11, a current I (ampere) flows through it for a particular period (t second). A work is said to be done by the moving stream of electrons (or charge) and is called electrical energy.

Thus, the total amount of work done in an electrical circuit is called electrical energy.

By definition, $$V = \frac{\text{Workdone}}{Q}$$

Therefore, work done or electrical energy expanded

$$VQ = VIt \text{ (since } I = Q/t\text{)}$$

Work / Energy / Power

$$= I^2Rt = \frac{V^2}{R}t$$

where V = potential difference in volt;
I = current in ampere;
t = time in second; and
R = resistance in ohm.

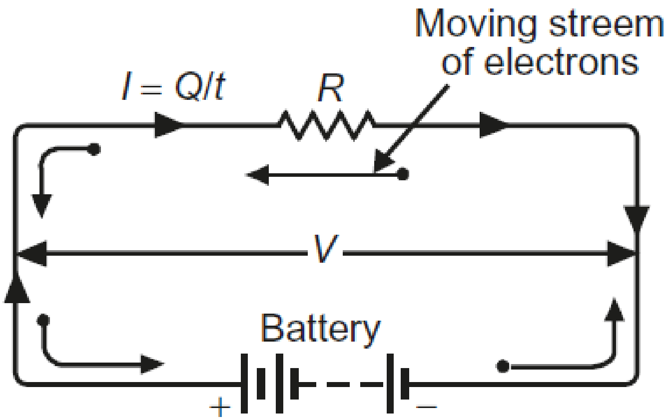


Fig. 1.11 Electrical energy consumed in a circuit

Units: The basic unit of electrical energy is joule (or Watt- second).

If, $V = 1$ V, $I = 1$ A, and $t = 1$ second

Then, electrical energy = 1 joule

Hence, the energy expanded in an electrical circuit is said to be one joule (or 1 watt-second) if one ampere current flows through the circuit for one second when a potential difference of 1 V is applied across it.

However, the practical or commercial unit of electrical energy is kilowatt-hour (kWh) which is also known as B.O.T. (Board of Trade) unit.

$$1 \text{ kWh} = 1000 \times 60 \times 60 \text{ watt-second} = 36 \times 10^5 \text{ Ws or joule}$$

Usually, 1 kWh is called one unit.

Work / Energy / Power

ELECTRICAL POWER

The rate at which work is being done in an electrical circuit is called electrical power.

$$\text{Hence, electrical power} = \frac{\text{Work done in an electric circuit}}{\text{Time}}$$

$$P = \frac{VIt}{t} = VI = I^2R = \frac{V^2}{R}$$

Unit: The unit of electrical power is watt (W).

If, $V = 1$ volt and $I = 1$ A. Then, $P = 1$ W.

Thus, the power consumed in an electrical circuit is said to be 1 W if 1 A current flows through the circuit when a potential difference of 1 V is applied across it.

However, the bigger unit of electrical power is kilowatt (kW), it is usually used in the power system.

$$1 \text{ kW} = 1000 \text{ W}$$

Work / Energy / Power

HEAT ENERGY

The form of energy which produces a sensation of warmth is called heat.

Mathematically,

Heat, $H = m\,S\,\theta$

Where m = mass of the body;

S = specific heat of the body; and

θ = rise or fall in temperature.

Unit: The unit of heat is kilocalorie (kcal)

If, $m = 1$ kg; $\theta = 1°C$, and $S = 1$, that is, specific heat of water.

Then, $H = 1$ kcal

Hence, the amount of heat required to raise the temperature of 1 kg of water through 1°C is called one kilocalorie.

However, the smaller unit of heat energy is calorie.

One calorie is defined as the amount of heat required to raise the temperature of 1 gram of water through 1°C.

$$1 \text{ kilocalorie} = 1000 \text{ calories}$$

Work / Energy / Power

MECHANICAL WORK

When a body, to which force is applied, moves in or opposite direction of the applied force, work is said to be done by or against the body.

Mathematically, Work = Force × distance or $W = F \times d$

Unit: The unit of work is Newton metre (Nm) or joule.

If, $F = 1$ N and $d = 1$ m; then, $W = 1$ Nm or joule.

Thus, when a force of 1 N applied on the body moves it to a distance of 1 m, the work done on the body is said to be 1 Nm or joule.

MECHANICAL POWER

The rate of doing work or the amount of work done per unit time is called power, that is,

$$\text{Power} = \frac{\text{Work done}}{\text{Time}}$$

Unit: The unit of mechanical power is Newton metre per second (i.e., Nm/s) or joule/second (i.e., J/s).

However, the practical unit of mechanical power is horse power.

In fact, the rate of doing 75 kg m of work per second is known as one horse power.

Work / Energy / Power

JOULES LAW OF ELECTRICAL HEATING

Joule (James Prescott Joule) established that there exists a definite relation between electrical energy expended and amount of heat produced. Thus, the relation is called Joule's law of electrical heating.

This law stated that the amount of heat produced (H) is directly proportional to the electrical energy expended (W).

That is, $$H \propto W \quad \text{or} \quad \frac{W}{H} = \text{J (constant)} \qquad (1.11)$$

Where J is a constant called mechanical equivalent of heat and its value is determined as 4.18 joule per calorie (i.e., 1 calorie = 4.18 joule). It means that to produce one calorie of heat, 4.18 J of electrical energy is expended.

From equation (1.8), we get,

$$H = \frac{W}{\text{J}} \quad \text{or} \quad H = \frac{I^2 Rt}{4.18} \text{calorie}$$

where I^2Rt is the electrical energy in joule.

Work / Energy / Power

RELATION BETWEEN VARIOUS QUANTITIES

Some of the important relations between various electrical, mechanical, and thermal (heat) quantities are given below:

Relation between Horse Power and kW

By definition, $1 \text{ H.P.} = 75 \text{ kg wt m/s}$

$= 75 \times 9.81$ Nm/s or joule/s or watt

$= 735.5$ W, that is, $1 \text{ H.P.} = 0.7355 \text{ kW}$

Relation between Horse Power and Torque

If a rotor of a radius r m rotates at a speed of N r.p.m. The force acting on the rotor tangential to its radius is F newton, then

$$\text{Work done in one rotation} = \text{Force} \times \text{distance covered/rev}$$

$$= F \times 2\pi r = 2\pi T \text{ Nm or joule}$$

where T is the torque, that is, moment acting on the rotor.

Work done/minute $= 2\pi NT$ (since N revolutions are made in one minute)

$$\text{Work done/sec or power} = \frac{2\pi NT}{60} \text{ joule/s or watt}$$

Work / Energy / Power

$$\therefore \text{H.P.} = \frac{2\pi NT}{60 \times 735.5} \text{(because 1 H.P. = 735.5 W)}$$

Relation between kWh and kcal

Since, $\quad 1 \text{ kWh} = 1000 \times 60 \times 60 \text{ Ws or joule}$

$$= \frac{36 \times 10^5}{4.18} \text{calorie} = \frac{36 \times 10^5}{4.8 \times 1000} \text{kcal}$$

$\therefore \quad 1 \text{ kWh} = 860 \text{ kcal}$

Work / Energy / Power

Example

An electric kettle was marked 500 W, 230 V and was found to take 13 minute to bring 1 kg of water at 20°C to boiling point. Determine the heat efficiency of the kettle.

Solution:

Heat absorbed by water, that is, output of kettle,

$$H = m\,S\theta$$

where $m = 1 \text{ kg} = 1000 \text{ g};\ S = 1;\ \theta = t_2 - t_1 = 100 - 20 = 80°\text{C}$

$\therefore$ $H = 1000 \times 1 \times 80 = 80000$ calorie

Energy input to kettle = Power × time

$= 500 \times 13 \times 60 = 390000$ wattsec or joule

$= 390000/4.18$ calorie $= 93301$ calorie

$$\text{Heat efficiency of kettle} = \frac{\text{Heat utilized by water}}{\text{Heat produced by kettle}} = \frac{80000}{93301} = 85.74\%\ (\text{Ans.})$$

Work / Energy / Power

Example

A geyser heater rated at 3 kW is used to heat its copper tank weighing 20 kg and holds 80 L of water. How long will it take to raise the temperature of water from 10°C to 60°C, if 20 per cent of energy supplied is wasted in heat losses?

Assuming specific heat of copper to be 0.095 and 4.2 joule to be equivalent to one calorie.

Solution

Mass of water, $m_1 = 80$ kg (since 1 L of water weighs 1 kg)

Mass of tank, $m_2 = 20$ kg

Specific heat of copper, $S_2 = 0.095$

Change in temperature, $\theta = (t_2 - t_1) = 60 - 10 = 50°C$

Heat utilized to raise the temperature of water and tank or output

$$= m_1 S_1 \theta + m_2 S_2 \theta = 80 \times 1 \times 50 + 20 \times 0.095 \times 50$$

$$= 4095 \text{ kcal} = 4095 \times 10^3 \times 4.2 \text{ joule}$$

Work / Energy / Power

Thermal efficiency, $\eta = 80\%$ (since loss = 20%)

$\therefore$

$$\text{Input energy} = \frac{\text{Output}}{\eta} = \frac{4095 \times 10^3 \times 4.2}{0.8} \text{ joule}$$

$$= \frac{4095 \times 10^3 \times 4.2}{0 \times 8 \times 36 \times 10^5} \text{kWh} = 5.973 \text{ kWh}$$

Time required to increase the temperature

$$= \frac{\text{Input energy}}{\text{Power}} = \frac{5.973}{3} = 1.991 \text{ hour (Ans.)}$$

Work / Energy / Power

Example *Two heater A and B are in parallel across supply voltage V. Heater A produces 500 kcal in 20 min. and B produces 1000 kcal in 10 min. The resistance of A is 10 ohm. What is the resistance of B ? If the same heaters are connected in series across the voltage V, how much heat will be prduced in kcal in 5 min ?*

Solution. Heat produced $= \dfrac{V^2 t}{JR}$ kcal

For heater A, $$500 = \frac{V^2 \times (20 \times 60)}{10 \times J} \quad \ldots(i)$$

For heater B, $$1000 = \frac{V^2 \times (10 \times 60)}{R \times J} \quad \ldots(ii)$$

From Eq. (i) and (ii), we get, $R =$ **2.5 Ω**

When the two heaters are connected in series, let H be the amount of heat produced in kcal. Since combined resistance is $(10 + 2.5) = 12.5\ \Omega$, hence

$$H = \frac{V^2 \times (5 \times 60)}{12.5 \times J} \quad \ldots(iii)$$

Dividing Eq. (iii) by Eq. (i), we have H = **100 kcal.**

Work / Energy / Power

Example

A hydroelectric power station operates at a mean heat of 25 m and is supplied from a reservoir having area of 6 sq. km. Calculate the energy produced by the water if the water level in the reservoir decreases by 1 m. The overall efficiency of the power station may be considered 80 per cent.

Solution:

Area of reservoir = $6 \text{ km}^2 = 6 \times 10^6 \text{ m}^2$

Decrease in water level = 1 m

Volume of water used = $6 \times 10^6 \times 1 = 6 \times 10^6 \text{ m}^3$

Mass of water, $m = 6 \times 10^6 \times 1000$ kg (1 m^3 of water weighs 1000 kg)

Height of water fall or head, $H = 25$ m

Potential energy of water fall = mgH

$$= 6 \times 10^9 \times 9.81 \times 25 \quad (g = 9.81)$$

$$= 14.715 \times 10^8 \text{ Nm}$$

Energy utilized to generate electrical energy, that is,

$$\text{Output} = \text{Input} \times \eta = \frac{14715 \times 10^8 \times 80}{100} \text{ Nm or joules}$$

$$= \frac{14715 \times 10^8 \times 80}{100 \times 1000 \times 60 \times 60} = 3,27,000 \text{ kWh (Ans.)}$$

Work / Energy / Power

Example

A diesel electric generating set supplies an output of 100 kW. The calorific value of the fuel oil used is 12500 kcal/kg. If overall efficiency of the unit is 36 per cent, (1) calculate the mass of oil required per hour and (2) the electrical energy generated per tonne of the fuel.

Solution:

Calorific value: The heat produced by the complete combustion of 1 kg of fuel is called the calorific value of the fuel.

$$\text{Output} = 100 \text{ kW}$$

$$\text{Energy delivered/hour} = 100 \times 1 = 100 \text{ kWh}$$

$$\text{Energy input} = \frac{\text{Output}}{\eta} = \frac{100 \times 100}{36} = 277.78 \text{ kWh}$$

$$\text{Heat energy required} = 277.78 \times 860 \text{ kcal} = 238889 \text{ kcal}$$

$$\text{Fuel required/hour} = \frac{\text{Heat produced}}{\text{Calorific value of the fuel}} = \frac{238889}{12500} = 19.11 \text{ kg (Ans.)}$$

$$\text{Heat produced/tonne of fuel} = 12500 \times 1000 \text{ kcal}$$

$$\text{Electrical energy generated} = \frac{\text{Heat produced}}{860} \times \eta = \frac{12500 \times 1000}{860} \times \frac{36}{100}$$

$$= 5232.56 \text{ kWh (Ans.)}$$

Concepts of Circuit Theory

SERIES CIRCUITS

In the circuit, a number of resistors are connected end to end so that same current flows through them is called series circuit.

Figure 1.14 shows a simple series circuit. In the circuit, three resistors R_1, R_2, and R_3 are connected in series across a supply voltage of V volt. The same current (I) is flowing through all the three resistors.

If V_1, V_2, and V_3 are the voltage drops across the three resistors R_1, R_2, and R_3, respectively, then

$$V = V_1 + V_2 + V_3 = IR_1 + IR_2 + IR_3 \text{ (Ohm's law)}$$

Let 'R' be the total resistance of the circuit, then

$$IR = IR_1 + IR_2 + IR_3 \quad \text{or} \quad R = R_1 + R_2 + R_3$$

that is, Total resistance = Sum of the individual resistances.

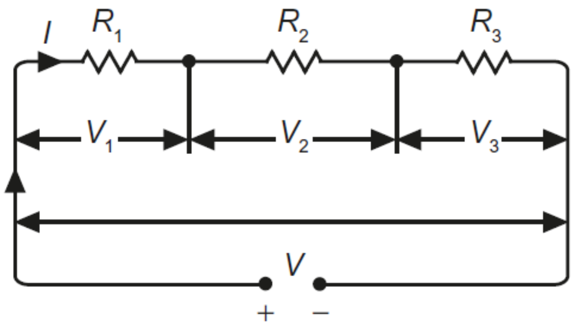


Fig. 1.14 Resistors connected in series

The common application of this circuit is in the marriages for decoration purposes where a number of low-voltage lamps are connected in series. In this circuit, all the lamps are controlled by a single switch, and they cannot be controlled individually. In domestic, commercial, and industrial wiring system, the main switch and fuses are connected in series to provide the necessary control and protection.

Concepts of Circuit Theory

PARALLEL CIRCUITS

In this circuit, one end of all the resistors is joined to a common point and the other ends are also joined to another common point so that different current flows through them is called parallel circuit.

Figure 1.15 shows a simple parallel circuit. In this circuit, three resistors R_1, R_2, and R_3 are connected in parallel across a supply voltage of V volt. The current flowing through them is I_1, I_2, and I_3, respectively.

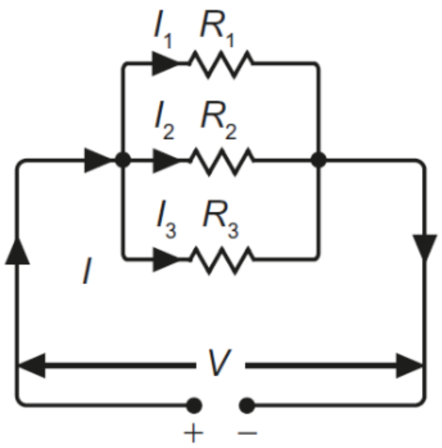


Fig. 1.15 Resistors connected in parallel

The total current drawn by the circuit,

$$I = I_1 + I_2 + I_3 = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \quad \text{(according to Ohm's law)}$$

Let 'R' be the total or effective resistance of the circuit, then

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \quad \text{or} \quad \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

that is, Reciprocal of total resistance = sum of reciprocal of the individual resistances.

All the appliances are operated at the same voltage, and therefore, all of them are connected in parallel. Each one of them can be controlled individually with the help of a separate switch.

Concepts of Circuit Theory

SERIES–PARALLEL CIRCUITS

The circuit in which series and parallel circuits are connected in series is called series–parallel circuit.

Figure 1.16 shows a simple series–parallel circuit. In this circuit, two resistors R_1 and R_2 are connected in parallel with each other across terminals AB. The other three resistors R_3, R_4, and R_5 are connected in parallel with each other across terminal BC. The two groups of resistors R_{AB} and R_{BC} are connected in series with each other across the supply voltage of V volt.

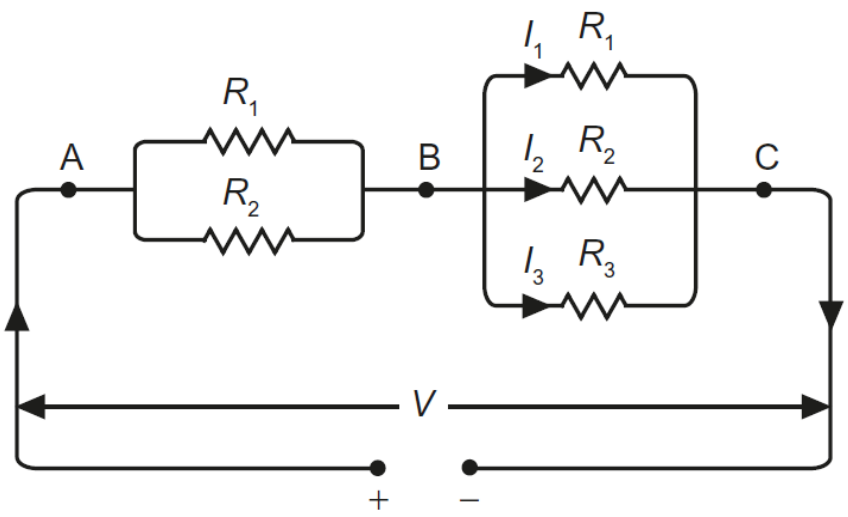


Fig. 1.16 Resistors connected in series-parallel combination

The total or effective resistance of the whole circuit can be determined as given below:

$$\frac{1}{R_{AB}} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{R_1 + R_2}{R_1 R_2} \text{ or } R_{AB} = \frac{R_1 R_2}{R_1 + R_2}$$

Similarly, $$\frac{1}{R_{BC}} = \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5} = \frac{R_3 R_4 + R_4 R_5 + R_5 R_3}{R_3 R_4 R_5} \text{ or } R_{BC} = \frac{R_3 R_4 R_5}{R_3 R_4 + R_4 R_5 + R_5 R_3}$$

Total or effective resistance of the circuit, $R = R_{AB} + R_{BC}$

Concepts of Circuit Theory

DIVISION OF CURRENT IN PARALLEL CIRCUITS

In parallel circuits, current is divided depending upon the value of resistors and the number of branches as discussed below.

When Two Resistors are Connected in Parallel

Figure 1.17 shows two resistors having resistance R_1 and R_2 connected in parallel across supply voltage of V volt. Let the current in each branch be I_1 and I_2, respectively.

According to Ohm's law, $I_1R_1 = I_2R_2 = V$ or $\dfrac{I_1}{I_2} = \dfrac{R_2}{R_1}$

Hence, the current in each branch of a parallel circuit is inversely proportional to its resistance. The value of branch current can also be expressed in terms of total circuit current, that is,

$$I_1R_1 = I_2R_2 = IR = V$$

where R is total or effective resistance of the circuit and I is the total current.

$$R = \frac{R_1R_2}{R_1 + R_2}$$

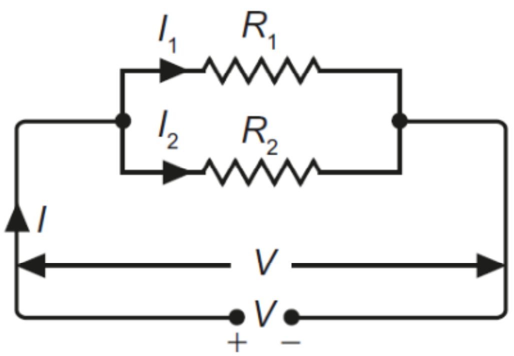


Fig. 1.17 Division of current in two resistors connected in parallel

Concepts of Circuit Theory

Now, $$I_1R_1 = IR = I\frac{R_1R_2}{R_1+R_2} \quad \text{or} \quad I_1 = I\frac{R_2}{R_1+R_2}$$

Similarly, $$I_2 = I\frac{R_1}{R_1+R_2}$$

When Three Resistors are Connected in Parallel

Now, $$R = \frac{R_1R_2R_3}{R_1R_2+R_2R_3+R_3R_1}$$

Figure 1.18 shows three resistors having resistance R_1, R_2, and R_3 connected in parallel across a supply voltage of V volt. Let the current in each branch be I_1, I_2, and I_3, respectively.

According to Ohm's law,

$$I_1R_1 = I_2R_2 = I_3R_3 = IR = V$$

Where R is the total or effective resistance of the circuit and I is the total current.

Now, $$R = \frac{R_1R_2R_3}{R_1R_2+R_2R_3+R_3R_1}$$

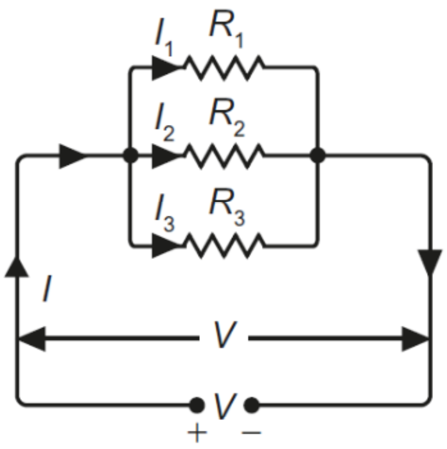


Fig. 1.18 Division of current in three resistors connected in parallel

Concepts of Circuit Theory

$\therefore$ $$I_1R_1 = IR = I \times \frac{R_1R_2R_3}{R_1R_2 + R_2R_3 + R_3R_1}$$

or $$I_1 = I \times \frac{R_2R_3}{R_1R_2 + R_2R_3 + R_3R_1}$$

Similarly, $$I_2 = I \times \frac{R_1R_3}{R_1R_2 + R_2R_3 + R_3R_1}$$

and $$I_3 = I \times \frac{R_1R_2}{R_1R_2 + R_2R_3 + R_3R_1}$$

Concepts of Circuit Theory

Example

Determine current I in the circuit shown in Figure 1.21, if all the resistors are given in ohms.

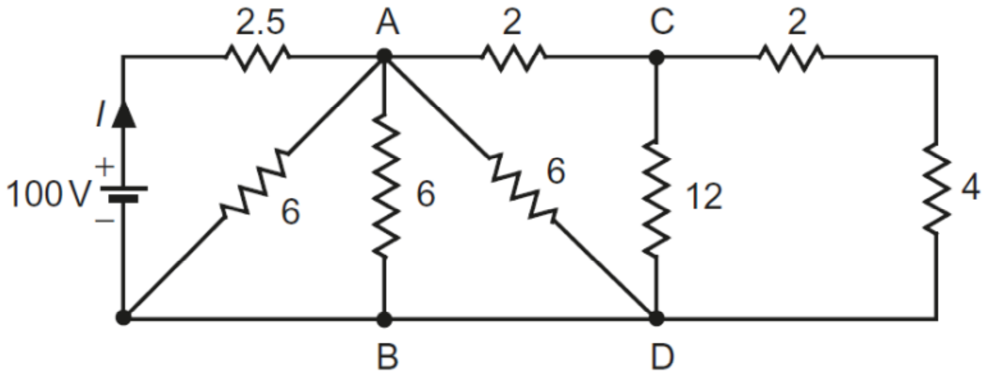


Fig. 1.21 Circuit diagram as per data

Solution:

To solve this type of circuit, start from the far end of the supply. A simplified circuit is shown in Figure 1.22.

The far end resistors of value 2 Ω and 4 Ω are connected in series with each other. Let their effective value be R_1 ohms.

∴ $$R_1 = 2 + 4 = 6\ \Omega$$

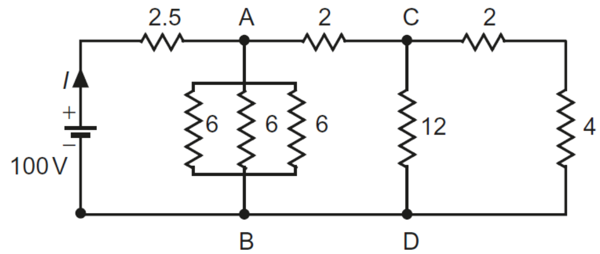


Fig. 1.22 Simplified circuit

Concepts of Circuit Theory

Then 12 Ω resistor and R_1 are connected in parallel with each other (Figure 1.23). Let their effective value be R_{CD}.

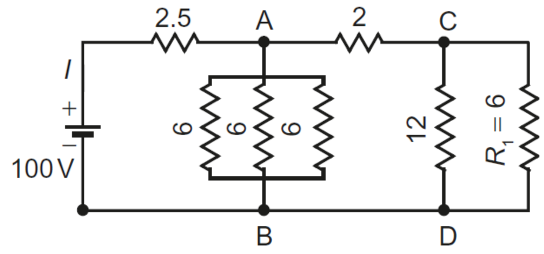


Fig. 1.23 Simplified circuit

$$\therefore \qquad R_{CD} = \frac{6 \times 12}{6+12} = 4\ \Omega$$

This resistance (R_{CD}) is connected in series with 2 Ω resistor as shown in Figure 1.24. Their effective value is say R_2.

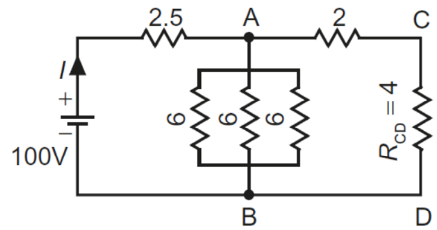


Fig. 1.24 Simplified circuit

$$\therefore \qquad R_2 = 2 + 4 = 6\ \Omega$$

This resistance (R_2) is connected in parallel with the three resistors of 6 Ω each already connected in parallel as shown in Figure 1.25. Their effective value is say R_{AB}.

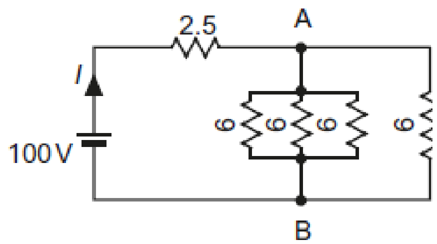


Fig. 1.25 Simplified circuit

$$R_{AB} = \frac{6}{4} = 1.5\ \Omega$$

Concepts of Circuit Theory

This resistance (R_{AB}) is connected in series with 2.5 Ω resistor as shown in Figure 1.26. The total resistance of the circuit is say R ohm.

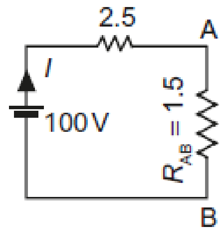


Fig. 1.26 Simplified circuit

Then, $$R = 2.5 + 1.5 = 4\ \Omega$$

$\therefore$ $$\text{Current, } I = \frac{V}{R} = \frac{100}{4} = 25\ \text{A (Ans.)}$$

Concepts of Circuit Theory

Example

A circuit consists of three resistances of 12 ohm, 18 ohm, and 3 ohm, respectively, joined in parallel is connected in series with a fourth resistance. The whole circuit is supplied at 60 V and it is found that power dissipated in 12 ohm resistance is 36 W. Determine the value of fourth resistance and the total power dissipated in the group.

Solution:

The circuit diagram is shown in Figure 1.20.

Power dissipated in 12 ohm resistor, $P_1 = 36$ W.
If the current in this resistor is I_1 ampere,

then, $$I_1^2 \times 12 = P_1$$

$$I_1^2 = \frac{36}{12} = 3 \quad \text{or} \quad I_1 = \sqrt{3} = 1.732 \text{ A}$$

Voltage across parallel resistors, $V_1 = I_1 \times 12$

$$= 1.732 \times 12 = 20.785 \text{ V}$$

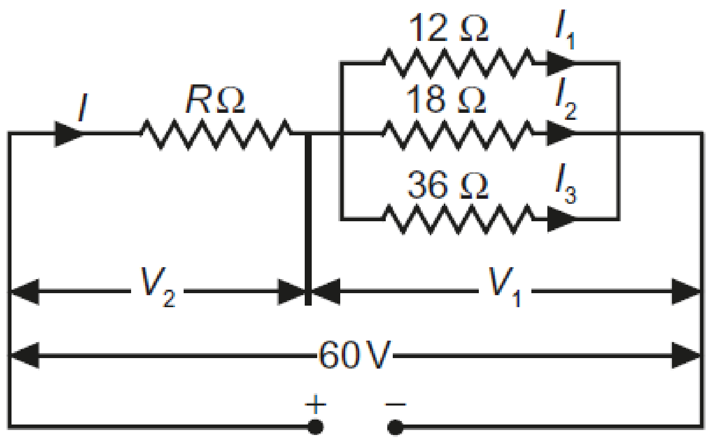
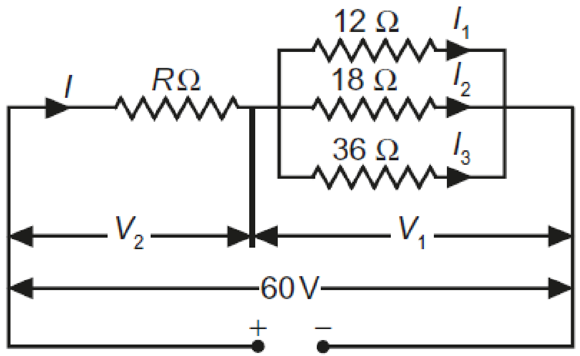


Fig. 1.20 Circuit diagram as per data

Concepts of Circuit Theory



Current in 18 ohm resistor,

$$I_2 = \frac{V_1}{18} = \frac{20.785}{18} = 1.155 \text{ A}$$

Current in 36 ohm resistor, $$I_3 = \frac{V_1}{36} = \frac{20.785}{36} = 0.577 \text{ A}$$

Current in resistor R, $$I_1 + I_2 + I_3 = 1.732 + 1.155 + 0.577 = 3.464 \text{ A}$$

Voltage across resistor R, $$V_2 = 60 - V_1 = 60 - 20.785 = 39.215 \text{ V}$$

$\therefore$ Value of series resistor, $$R = \frac{V_2}{I} = \frac{39.215}{3.464} = 11.32 \text{ ohm (Ans.)}$$

DC Circuit Analysis

ELECTRIC NETWORK

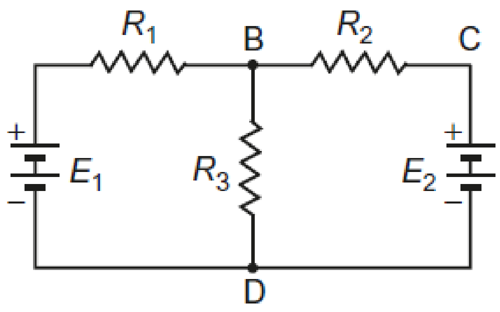


Fig. 2.1 An electric network

A simple electric network is shown in Figure 2.1. It contains two voltage sources E_1 and E_2 and three resistors R_1, R_2, and R_3. In fact, the interconnection of either passive elements or the interconnection of active and passive elements constitute an electric network.

Active elements

The elements that supply energy in an electric network are called active elements.
In the circuit shown in Figure 2.1, E_1 and E_2 are the active elements.

Note: When a battery is delivering current from its positive terminal, it is under discharging condition. However, if it is receiving current at its positive terminal, then it is under charging condition. In both the cases, it will be considered as an active element.

Passive Elements

The elements that receive electrical energy and dispose the same in their own way of disposal are called passive elements. In the circuit shown in Figure 2.1, R_1, R_2, and R_3 are the passive elements. The other passive elements that are not used in this circuit are inductors and capacitors.

DC Circuit Analysis

Network Terminology

Network theorems are applied to analyse the electrical network. While discussing these theorems, we come across the following terms:

1. **Electric network:** A combination of various electric elements connected in any manner is called an electric network.
2. **Electric circuit:** An electric circuit is a closed conducting path through which an electric current either flows or is intended to flow.
3. **Parameters:** The various elements of an electric circuit are called its parameters such as resistors, inductors, and capacitors.
4. **Linear circuit:** An electric circuit that contains parameters of constant value, that is, their value do not change with voltage or current is called linear circuit.
5. **Non-linear circuit:** An electric circuit that contains parameters whose value changes with voltage or current is called non-linear circuit.
6. **Bilateral circuit:** An electric circuit that possesses the same properties or characteristics in either direction is called bilateral circuit. A transmission line is bilateral because it can be made to perform its function equally well in either direction.
7. **Unilateral circuit:** An electric circuit whose properties or characteristics change with the direction of its operation is called unilateral circuit. A diode rectifier circuit is a unilateral circuit because it cannot perform similarly in both the directions.

DC Circuit Analysis

8. **Unilateral elements:** The elements that conduct only in one direction, such as semi-conductor diode, are called unidirectional elements.

9. **Bilateral elements:** The elements that conduct in both the directions similarly, such as a simple piece of wire (resistor), diac, and triac, are called bilateral elements.

10. **Active network:** An electric network that contains one or more sources of emf is called active network.

11. **Passive network:** An electric network that does not contain any source of emf is called passive network.

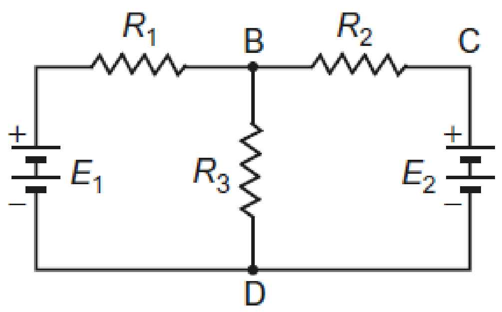


Fig. 2.1 **An electric network**

12. **Node:** A node is a point in the network where two or more circuit elements are joined. In Figure 2.1, A, B, C, and D are the nodes.

DC Circuit Analysis

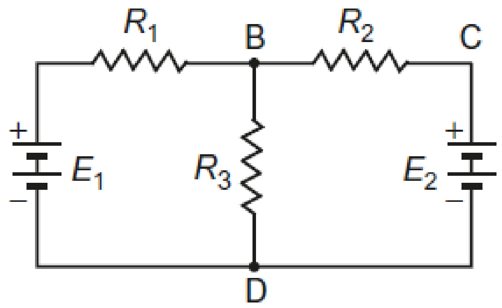


Fig. 2.1 An electric network

13. **Junction:** A junction is a point in the network where three or more circuit elements are joined. In fact, it is a point where current is divided. In Figure 2.1, B and D are junctions.

14. **Branch:** The part of a network that lies between two junction points is called branch. In Figure 2.1, DAB, BCD, and BD are the three branches.

15. **Loop:** The closed path of a network is called a loop. In Figure 2.1, ABDA, BCDB, and ABCDA are the three loops.

16. **Mesh:** The most elementary form of a loop that cannot be further divided is called a mesh. In Figure 2.1, ABDA and BCDB are the two meshes, but ABCDA is the loop.

Kirchhoff's Laws

LIMITATIONS OF OHM'S LAW

In a series circuit or in any branch of a simple parallel circuit the calculation of the current is easily effected by the direct application of Ohm's law. But such a simple calculation is not possible if one of the branches of a parallel circuit contains a source of e.m.f., or if the current is to be calculated in a part of a network in which sources of e.m.f. may be present in several meshes or loops forming the network. The treatment of such cases is effected by the application of fundamental principles of electric circuits. These principles were correlated by Kirchhoff many years ago and enunciated in the form of *two laws*, which can be considered as the foundations of circuit analysis. Other, later, methods have been developed, which when applied to special cases considerably shorten the algebra and arithmetic computation compared with the original Kirchhoff's method.

KIRCHHOFF'S LAWS

For complex circuit computations, the following two laws first stated by Gutsav R. Kirchhoff (1824–87) are indispensable.

(*i*) Kirchhoff's Point Law or Current Law (KCL). It states as follows :

The sum of the currents entering a junction is equal to the sum of the currents leaving the junction. Refer Fig. 27.

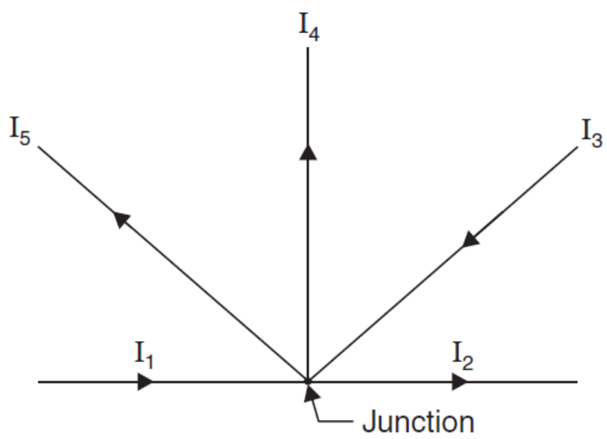


Fig. 27

Kirchhoff's Laws

If the currents *towards* a junction are considered *positive* and those *away* from the same junction *negative*, then this law states that the *algebraic sum of all currents meeting at a common junction is zero.*

i.e., Σ Currents entering = Σ Currents leaving

$$I_1 + I_3 = I_2 + I_4 + I_5 \qquad \text{...[20 (a)]}$$

or

$$I_1 + I_3 - I_2 - I_4 - I_5 = 0 \qquad \text{...[20 (b)]}$$

(*ii*) Kirchhoff's Mesh Law or Voltage Law (KVL). It states as follows :

The sum of the e.m.fs (rises of potential) around any closed loop of a circuit equals the sum of the potential drops in that loop.

Considering a rise of potential as positive (+) and a drop of potential as negative (–), the *algebraic sum* of potential differences (voltages) around a closed loop of a circuit is zero :

$$\Sigma E - \Sigma IR \text{ drops} = 0 \text{ (around closed loop)}$$

i.e.,

$$\Sigma E = \Sigma IR \qquad \text{...[21 (a)]}$$

or

$$\Sigma \text{ Potential rises} = \Sigma \text{ Potential drops} \qquad \text{...[21 (b)]}$$

To apply this law in practice, assume an arbitrary current direction for each branch current. The end of the resistor through which the current enters, is then positive, with respect to the other end. *If the solution for the current being solved turns out negative, then the direction of that current is opposite to the direction assumed.*

Kirchhoff's Laws

In tracing through any single circuit, whether it is by itself or a part of a network, the following **rules** must be applied :

1. A *voltage drop exists* when tracing through a resistance *with or in the same direction as the current*, or through a battery or generator against their voltage, that is from *positive (+) to negative (–)*. Refer Fig. 28.

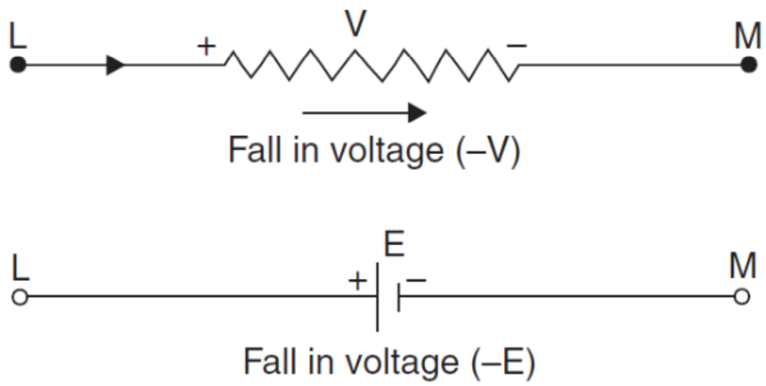


Fig. 28

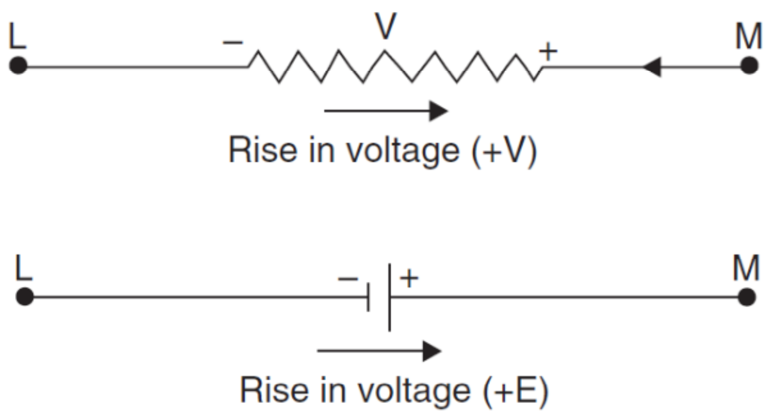


Fig. 29

2. A *voltage rise exists* when tracing through a resistance *against* or *in opposite direction to the current* or through a battery or a generator with their voltage that is from *negative (–) to positive (+)*. Refer Fig. 29.

Applications of Kirchhoff's Laws

APPLICATIONS OF KIRCHHOFF'S LAWS

Kirchhoff's laws may be employed in the following methods of solving networks :

1. Branch-current method
2. Maxwell's loop (or mesh) current method
3. Nodal voltage method.

Branch-Current Method

For a multi-loop circuit the following ***procedure*** is adopted for writing equations :

1. Assume currents in different branch of the network.

2. Write down the smallest number of voltage drop loop equations so as to include all circuit elements ; these loop equations are independent.

If there are n nodes of three or more elements in a circuit, then write $(n - 1)$ equations as per current law.

3. Solve the above equations simultaneously.

The assumption made about the directions of the currents initially is arbitrary. In case the actual direction is *opposite to the assumed one*, it will be reflected as a negative value for that current in the answer.

The branch-current method (the most primitive one) involves more labour and is not used *except for very simple circuits.*

Applications of Kirchhoff's Laws

Example *Find the magnitude and direction of currents in each of the batteries shown in Fig. 33.*

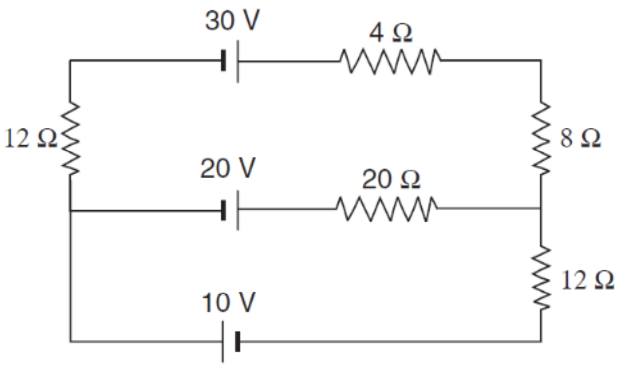


Fig. 33

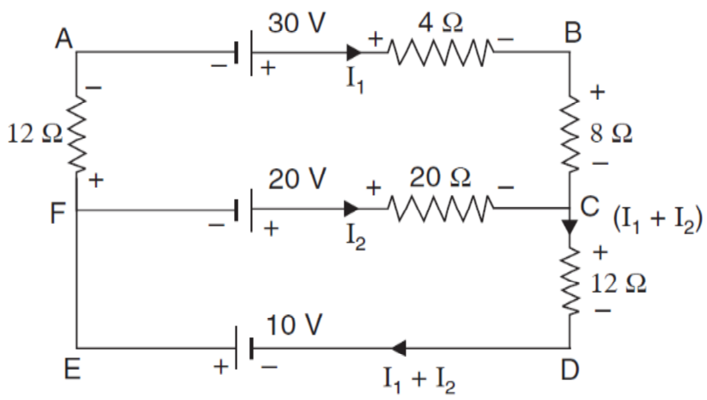


Fig. 34

Solution.

Let the directions of currents I_1, I_2 and I_3 in the batteries be as shown in Fig. 34.

Applying Kirchhoff's voltage law to the circuit **ABCFA**, we get

$$30 - 4I_1 - 8I_1 + 20I_2 - 20 - 12I_1 = 0$$

$$-24I_1 + 20I_2 + 10 = 0$$

or $$12I_1 - 10I_2 - 5 = 0 \qquad ...(i)$$

Circuit **ECDEF** gives,

$$20 - 20I_2 - 12(I_1 + I_2) + 10 = 0$$

$$20 - 20I_2 - 12I_1 - 12I_2 + 10 = 0$$

Applications of Kirchhoff's Laws

$$-12I_1 - 32I_2 + 30 = 0$$

or $$6I_1 + 16I_2 - 15 = 0 \quad \ldots(ii)$$

Multiplying eqn. (*ii*) by 2 and subtracting it from (*i*), we get

$$-42I_2 + 25 = 0$$

i.e., $$I_2 = 0.595 \text{ A}$$

Substituting this value of I_2 in eqn. (*i*), we get

$$12I_1 - 10 \times 0.595 - 5 = 0$$

or $$I_1 = 0.912 \text{ A}$$

Hence current through,

30 V battery, $I_1 = \mathbf{0.912\ A.}$ **(Ans.)**

20 V battery, $I_2 = \mathbf{0.595\ A.}$ **(Ans.)**

10 V battery, $(I_1 + I_2) = \mathbf{1.507\ A.}$ **(Ans.)**

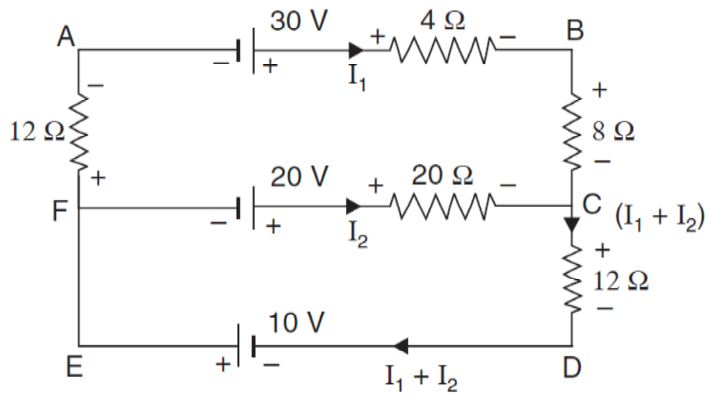


Fig. 34

Applications of Kirchhoff's Laws

Example *Determine the current in the 4 Ω resistance of the circuit shown in Fig. 40.*

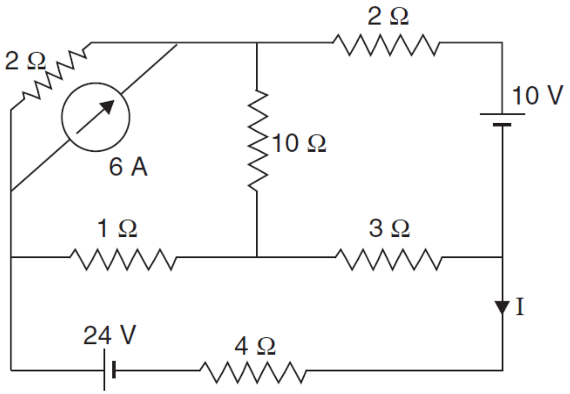


Fig. 40

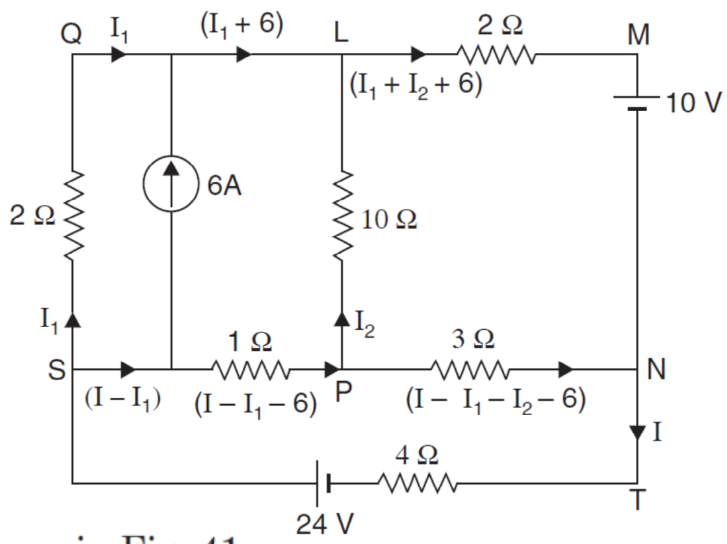


Fig. 41

Solution. Refer Fig. 41.

Let the directions of various currents in different circuits be as shown in Fig. 41.

Applying Kirchhoff's voltage law to the circuit **SQLPS**, we get

$$-2I_1 + 10I_2 + 1(I - I_1 - 6) = 0$$

$$I - 3I_1 + 10I_2 = 6 \quad \text{...(i)}$$

Circuit **LMNPL** gives,

$$-2(I_1 + I_2 + 6) - 10 + 3(I - I_1 - I_2 - 6) - 10I_2 = 0$$

$$3I - 5I_1 - 15I_2 = 40 \quad \text{...(ii)}$$

Applications of Kirchhoff's Laws

Circuit **SPNTS** gives,

$$-1(I - I_1 - 6) - 3(I - I_1 - I_2 - 6) - 4I + 24 = 0$$

$$-8I + 4I_1 + 3I_2 = -48$$

$$8I - 4I_1 - 3I_2 = 48 \qquad \text{...}(iii)$$

Multiplying eqn. (i) by 3 and subtracting eqn. (ii) from eqn. (i), we get

$$-4I_1 + 45I_2 = -22$$

or

$$I_1 - 11.25I_2 = 5.5 \qquad \text{...}(iv)$$

Multiplying eqn. (i) by 8 and subtracting eqn. (iii) from eqn. (i), we get

$$-20I_1 + 83I_2 = 0 \qquad \text{...}(v)$$

Multiplying eqn. (iv) by 20 and adding eqn. (v), we get

$$-142I_2 = 110$$

$$\therefore \qquad I_2 = -0.774 \text{ A}$$

and

$$I_1 = -3.212 \text{ A}$$

Substituting the values of I_1 and I_2 in eqn. (i), we get

$$I - 3 \times (-3.212) + 10 \times (-0.774) = 6$$

i.e., **I = 23.37 A. (Ans.)**

Applications of Kirchhoff's Laws

Example *Determine the current supplied by the battery in the circuit shown in Fig. 45.*

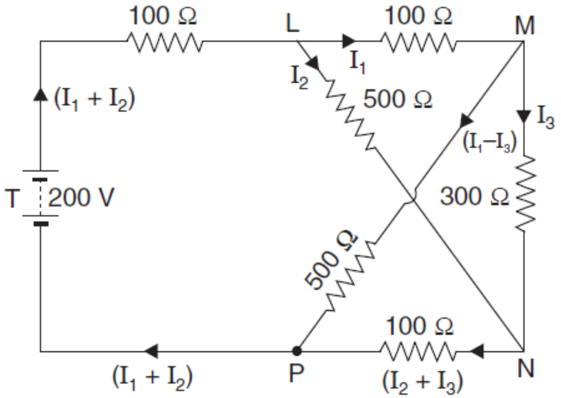


Fig. 45

Solution. Refer Fig. 45.

Applying Kirchhoff's voltage law to the circuit **LMNL**, we get

$$-100I_1 - 300I_3 + 500I_2 = 0$$

$$I_1 - 5I_2 + 3I_3 = 0 \qquad ...(i)$$

Circuit **MNPM** gives,

$$-300I_3 - 100(I_2 + I_3) + 500(I_1 - I_3) = 0$$

$$500I_1 - 100I_2 - 900I_3 = 0$$

$$I_1 - 0.2I_2 - 1.8I_3 = 0 \qquad ...(ii)$$

Applications of Kirchhoff's Laws

Circuit **LMPTL** gives,

$$-100I_1 - 500(I_1 - I_3) + 200 - 100(I_1 + I_2) = 0$$

$$-700I_1 - 100I_2 + 500I_3 = -200$$

$$I_1 + 0.143I_2 - 0.714I_3 = 0.286 \quad \text{...}(iii)$$

Multiplying (*i*) by 1.8 and (*ii*) by 3 and adding, we get

$$\begin{array}{r} 1.8I_1 - 9I_2 + 5.4I_3 = 0 \\ 3I_1 - 0.6I_2 - 5.4I_3 = 0 \\ \hline 4.8I_1 - 9.6I_2 = 0 \end{array}$$

or $$I_1 - 2I_2 = 0 \quad \text{...}(iv)$$

Multiplying (*ii*) by 0.714 and (*iii*) by 1.8 and subtracting, we get

$$\begin{array}{r} 0.714I_1 - 0.143I_2 - 1.285I_3 = 0 \\ 1.8I_1 + 0.257I_2 - 1.285I_3 = 0.515 \\ - \quad\quad - \quad\quad + \quad\quad\quad - \\ \hline -1.086I_1 - 0.4I_2 = -0.515 \end{array}$$

or $$I_1 + 0.368I_2 = 0.474 \quad \text{...}(v)$$

Subtracting (*v*) from (*iv*), we get $2.368I_2 = 0.474$

i.e., $I_2 = 0.2$ A

and $I_1 = 0.4$ A

$\therefore$ **Current supplied by the battery** $= I_1 + I_2 = 0.2 + 0.46 =$ **0.6 A. (Ans.)**

Applications of Kirchhoff's Laws

MAXWELL'S MESH CURRENT METHOD (LOOP ANALYSIS)

In this method, mesh or loop currents are taken instead of branch currents (as in Kirchhoff's laws). The following steps are taken while solving a network by this method:

1. The whole network is divided into number of meshes. Each mesh is assigned a current having continuous path (current is not split at a junction). These mesh currents are preferably drawn in clockwise direction. The common branch carries the algebraic sum of the mesh currents flowing through it.
2. Write KVL equation for each mesh using the same signs as applied to Kirchhoff's laws.
3. Number of equations must be equal to the number of unknown quantities. Solve the equations and determine the mesh currents.

Applications of Kirchhoff's Laws

Example

Using loop current method, find the current I_1 and I_2 as shown in Figure 2.43.

Solution:

Let the current flowing through the two loops be I_1 and I_2, as shown in Figure 2.44.

By applying KVL to different loops, we get

Loop ABEFA

$$-2I_1 - 6(I_1 - I_2) - 6 + 10 = 0$$

$$8I_1 - 6I_2 = 4$$

$$4I_1 - 3I_2 = 2 \qquad (2.29)$$

Loop BCDEB

$$-3I_2 - 2 + 6 - 6(I_2 - I_1) = 0$$

$$-6I_1 + 9I_2 = 4 \qquad (2.30)$$

Multiplying Equation (2.29) by 3 and Equation (2.30) by 2, we get

$$12I_1 - 9I_2 = 6 \qquad (2.31)$$

$$-12I_1 + 18I_2 = 8 \qquad (2.32)$$

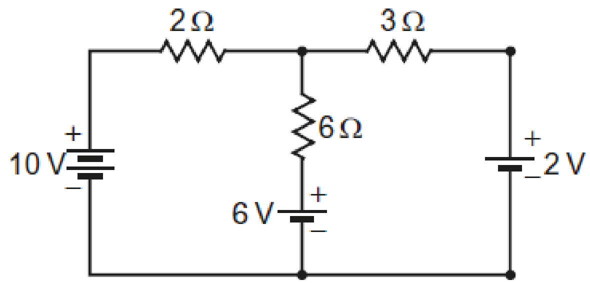


Fig. 2.43 Given network

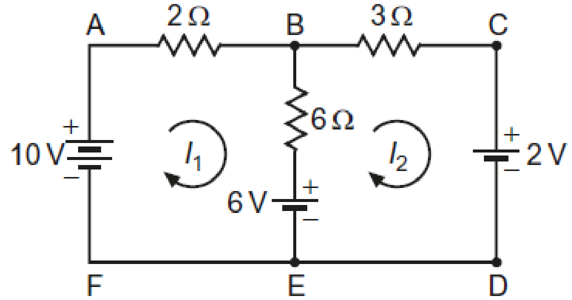


Fig. 2.44 Loop currents in various sections

Adding Equations (2.31) and (2.32), we get

$$I_1 = \frac{5}{3} = 1.667\text{A}$$

Applications of Kirchhoff's Laws

Example Using mesh current method, determine current I_x in the circuit shown in Figure 2.47.

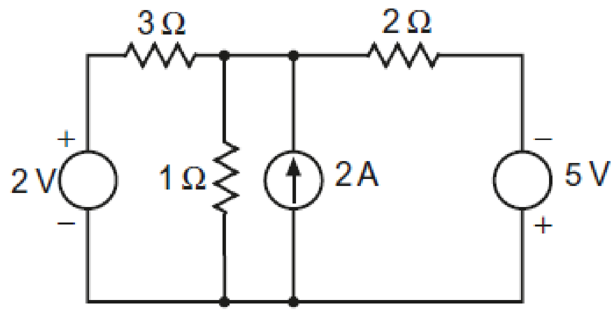


Fig. 2.47 Given network

Solution:

Let the circuit be as shown in Figure 2.48. Suppose voltage across 2 A current source is V_x,

By applying KVL in mesh 1; $3I_1 + (I_1 - I_2) = 2$

$$4I_1 - I_2 = 2 \tag{2.35}$$

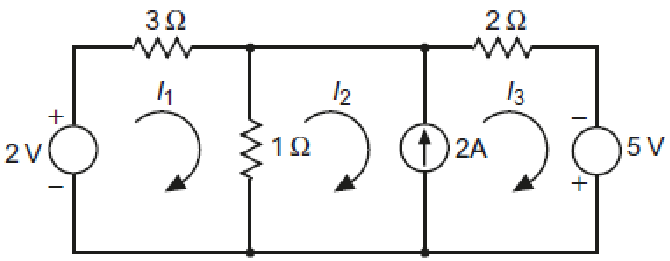


Fig. 2.48 Loop currents in various sections

By applying KVL in mesh 2; $(I_2 - I_1) + V_x = 0$

$$I_1 - I_2 = V_x \tag{2.36}$$

By applying KVL in mesh 3; $2I_3 = 5 + V_x$ (2.37)

Further, $$I_3 - I_2 = 2 \tag{2.38}$$

Applications of Kirchhoff's Laws

From Equations (2.36) and (2.37) $2I_3 = 5 + (I_1 - I_2)$

or $$-I_1 + I_2 + 2I_3 = 5 \qquad (2.39)$$

From Equations (2.35), (2.38), and (2.39),

In matrix form $$\begin{bmatrix} 4 & -1 & 0 \\ 0 & -1 & 1 \\ -1 & 1 & 2 \end{bmatrix}\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 2 \\ 2 \\ 5 \end{bmatrix} = 4\,(-2-1) + 1\,(0+1) = -11$$

$$\Delta = \begin{vmatrix} 4 & -1 & 0 \\ 0 & -1 & 1 \\ -1 & 1 & 2 \end{vmatrix} = 4\,(-2-1) + 1\,(0+1) = -11$$

$$\Delta_{11} = \begin{vmatrix} 2 & -1 & 0 \\ 2 & -1 & 1 \\ 5 & 1 & 2 \end{vmatrix} = 2\,(-2-1) - (-1)\,(4-5) = -7$$

$$\Delta_{12} = \begin{vmatrix} 4 & 2 & 0 \\ 0 & 2 & 1 \\ -1 & 5 & 2 \end{vmatrix} = 4\,(4-5) - (2)\,(0+1) = -4 - 2 = -6$$

Applications of Kirchhoff's Laws

$$I_1 = \frac{\Delta_{11}}{\Delta} = \frac{-7}{-11} = \frac{7}{11}\,\text{A}$$

$$I_2 = \frac{\Delta_{12}}{\Delta} = \frac{-6}{-11} = \frac{6}{11}\,\text{A}$$

$$\text{Current, } I_x = I_1 - I_2 = \frac{7}{11} - \frac{6}{11} = \frac{1}{11}\,\text{A}$$

Applications of Kirchhoff's Laws

NODAL ANALYSIS

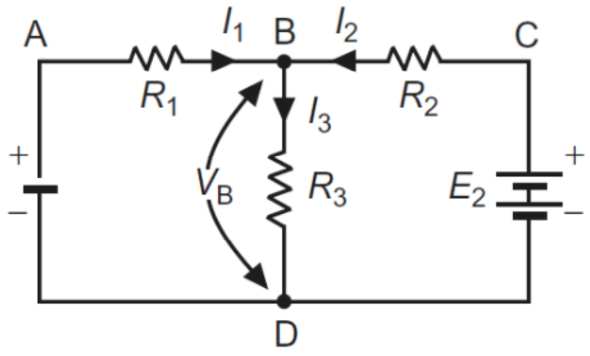


Fig. 2.49 Network with Node B and D

In this method, one of the nodes is taken as the reference node and the other as independent nodes. The voltages at the different independent nodes are assumed and the equations are written for each node as per KCL. After solving these equations, the node voltages are determined. Then, the branch currents are determined.

Consider a circuit shown in Figure 2.49, where D and B are the two independents nodes. Let D be the reference node and the voltage of node B be V_B.

According to KCL, $I_1 + I_2 = I_3$ (2.40)

In mesh ABDA, the potential difference across R_1 is $E_1 - V_B$

$$I_1 = \frac{E_1 - V_B}{R_1}$$

In mesh BCDB, the potential difference across R_2 is $E_2 - V_B$

$$I_2 = \frac{E_2 - V_B}{R_2}$$

Applications of Kirchhoff's Laws

Further, current, $I_3 = \dfrac{V_B}{R_3}$

Substituting these values in Equation (2.40), we get

$$\frac{E_1 - V_B}{R_1} = \frac{E_1 - V_B}{R_2} = \frac{V_B}{R_3}$$

Rearranging the terms,

$$V_B\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) - \frac{E_1}{R_1} - \frac{E_2}{R_2} = 0$$

Since all other value are known, except V_B, calculate the value of V_B. Then, determine the value of I_1, I_2, and I_3. This method is faster as the result are obtained by solving lesser number of equations.

Applications of Kirchhoff's Laws

Example

Using nodal analysis, find current I through 10-Ω resistor in Figure 2.53.

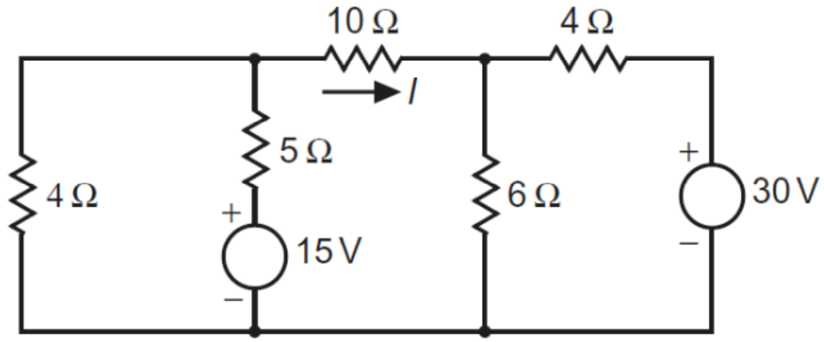


Fig. 2.53 Given network

Solution:

The independent nodes are A, B, and C. Let C be the reference node and V_A and V_B be the voltages at node A and B, respectively. Let us assume the direction of flow of current is as marked in Figure 2.54. By applying KCL at node A, we get

$$I_1 + I_2 = I$$

$$\frac{0 - V_A}{4} + \frac{15 - V_A}{5} = \frac{V_A - V_B}{10}$$

or $$-5V_A + 60 - 4V_A = 2V_A - 2V_B$$

or $$11V_A - 2V_B = 60 \quad (2.45)$$

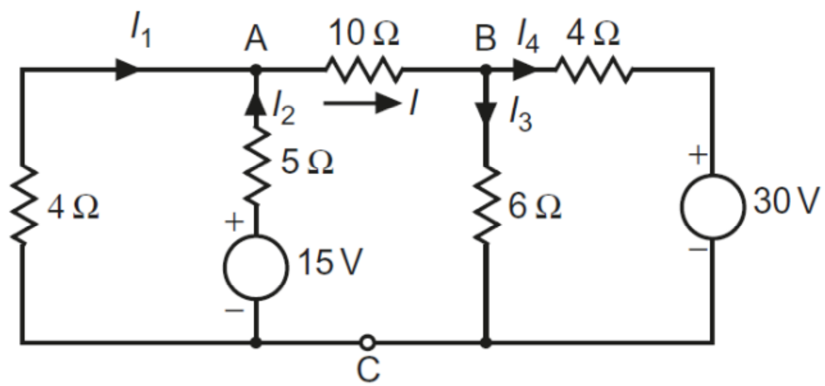


Fig.2.54 Assumed direction of flow of current in various branches

Applications of Kirchhoff's Laws

By applying KCL at node B, we get

$$I = I_4 + I_3$$

$$\frac{V_A - V_B}{10} = \frac{V_B - 30}{4} + \frac{V_B}{6}$$

or $$12V_A - 12V_B = 30V_B - 900 + 20V_B$$

or $$12V_A - 62V_B = -900 \qquad (2.46)$$

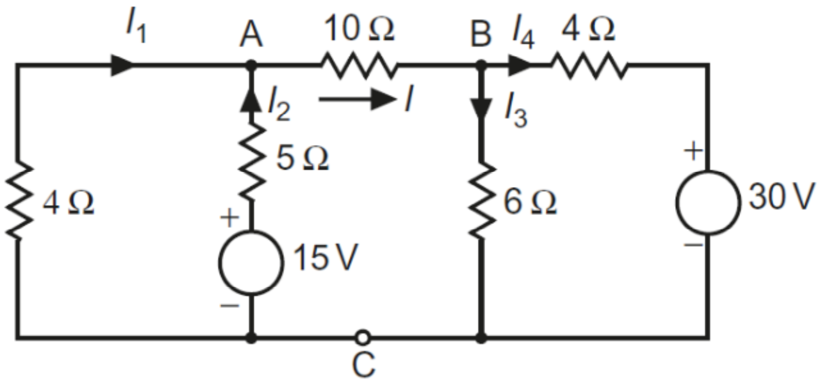


Fig.2.54 Assumed direction of flow of current in various branches

Solving Equation (2.45) and (2.46), we get

$$V_A = 8.39 \text{ V} \quad \text{and} \quad V_B = 16.14 \text{ V}$$

Current, $$I = \frac{V_A - V_B}{10} = \frac{8.39 - 16.14}{10} = \frac{-7.75}{10} = -0.775 \text{ A}$$

$$I = 0.775 \text{ A (from B to A)}$$

Applications of Kirchhoff's Laws

Example Use nodal analysis to find the current in various resistors of the circuit shown in Figure 2.57.

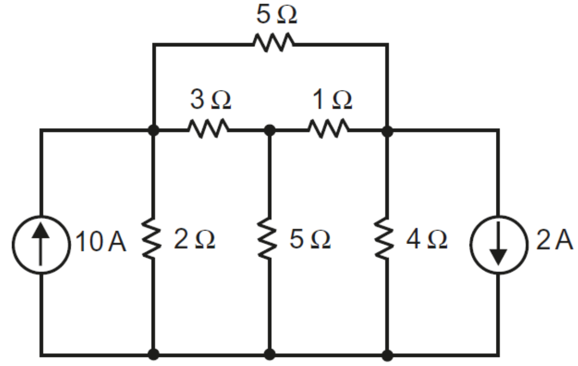


Fig. 2.57 Given network

Solution: The independent nodes are A, B, C, and D. Let D be the reference node and V_A, V_B, and V_C be the voltages at nodes A, B, and C, respectively, The current flowing through various branches are marked in Figure 2.58.

By applying KCL at different nodes, different node voltage equations are obtained as follows:

Node A

$$I_1 + I_2 + I_3 = I$$

$$\frac{V_A}{2} + \frac{V_A - V_B}{3} + \frac{V_A - V_C}{5} = 10$$

$$15V_A + 10(V_A - V_B) + 6(V_A - V_C) = 300$$

$$\text{or} \quad 31V_A - 10\,V_B - 6\,V_C = 300 \qquad (2.47)$$

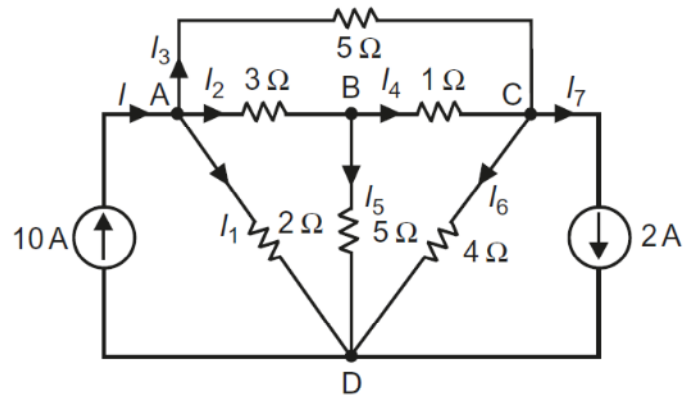


Fig. 2.58 Assumed direction of flow of current in various branches

Applications of Kirchhoff's Laws

Node B

$$I_2 - I_4 - I_5 = 0$$

$$\frac{V_A - V_B}{3} - \frac{V_B - V_C}{1} - \frac{V_B}{5} = 0$$

$$5\,(V_A - V_B) - 15\,(V_B - V_C) - 3\,V_B = 0$$

or $$5V_A - 23\,V_B + 15\,V_C = 0 \qquad (2.48)$$

Node C

$$I_3 + I_4 - I_6 - I_7 = 0$$

$$\frac{V_A - V_C}{5} + \frac{V_B - V_C}{1} - \frac{V_C}{4} - 2 = 0$$

$$4\,(V_A - V_C) + 20\,(V_B - V_C) - 5V_C - 40 = 0$$

$$\text{or } 4V_A + 20\,V_B - 29\,V_C = 40 \qquad (2.49)$$

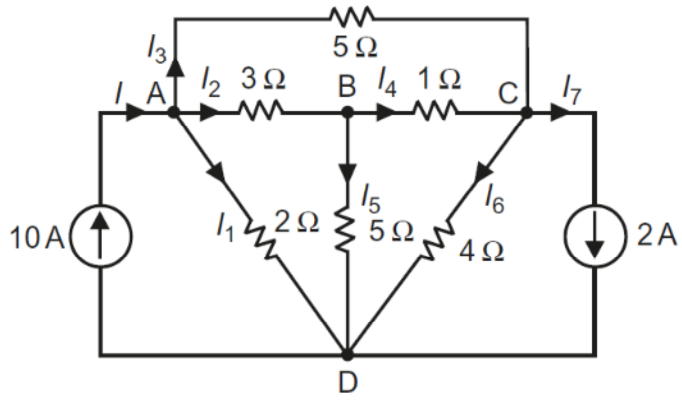


Fig. 2.58 Assumed direction of flow of current in various branches

Applications of Kirchhoff's Laws

The three equations in matrices form are:

$$\begin{bmatrix} 31 & -10 & -6 \\ 5 & -23 & 15 \\ 4 & 20 & -29 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} 300 \\ 0 \\ 40 \end{bmatrix}$$

$$D_0 = \begin{bmatrix} 31 & -10 & -6 \\ 5 & -23 & 15 \\ 4 & 20 & -29 \end{bmatrix} = 31\,(667 - 300) + 10\,(-145 - 60) - 6\,(100 + 92)$$

$$= 11{,}377 - 2{,}050 - 1{,}152 = 8{,}175$$

$$D_1 = \begin{bmatrix} 300 & -10 & -6 \\ 0 & -23 & 15 \\ 40 & 20 & -29 \end{bmatrix} = 300\,(667 - 300) + 10\,(-600) - 6\,(+920)$$

$$= 110{,}100 - 6{,}000 - 5{,}520 = 98{,}580$$

$$D_2 = \begin{bmatrix} 31 & 300 & -6 \\ 5 & 0 & 15 \\ 4 & 40 & -29 \end{bmatrix} = 31\,(0 - 600) - 300\,(-145 - 60) - 6\,(200)$$

$$= -18{,}600 + 61{,}500 - 1{,}200 = 41{,}700$$

Applications of Kirchhoff's Laws

$$D_3 = \begin{bmatrix} 31 & -10 & 300 \\ 5 & -23 & 0 \\ 4 & 20 & 40 \end{bmatrix} = 31\,(-920-0) + 10\,(200-0) + 300\,(100+92)$$

$$= -28{,}520 + 2{,}000 + 57{,}600 = 31{,}080$$

$$V_A = \frac{D_1}{D_0} = \frac{98{,}580}{8{,}175} = 12.06; \qquad V_B = \frac{D_2}{D_0} = \frac{41{,}700}{8{,}175} = 5.1\,\text{V} \qquad V_C = \frac{D_3}{D_0} = \frac{31{,}080}{8{,}175} = 3.802\,\text{V}$$

Current in various resistors:

$$I_1 = \frac{V_A}{2} = \frac{12.06}{2} = 6.03\,\text{A}; \quad I_2 = \frac{V_A - V_B}{3} = \frac{12.06 - 5.1}{3} = 2.32\,\text{A};$$

$$I_3 = \frac{V_A - V_C}{5} = \frac{12.06 - 3.802}{5} = 1.652\,\text{A}; \quad I_4 = \frac{V_B - V_C}{1} = \frac{5.1 - 3.802}{1} = 1.298\,\text{A};$$

$$I_5 = \frac{V_B}{5} = \frac{5.1}{5} = 1.02\,\text{A}; \qquad I_6 = \frac{V_C}{4} = \frac{3.802}{4} = 0.95\,\text{A}$$

Electromagnetic Induction & Lenz's Law

ELECTROMAGNETIC INDUCTION AND FORCE

In this section, certain fundamental laws of electromagnetism will be enunciated and also certain rules will be put forth which are helpful in application of the laws.

I Faraday's Law

Flux Linkages

If flux ϕ passes through all the N turns of a coil as shown in Fig. 5.13, the flux is said to link the coil.

The flux linkage of the coil are

$$\lambda = N\phi \text{ Weber-turns (Wb-T)} \tag{5.19}$$

The Faraday's law states that if the magnitude of the flux through the coil changes with time, an *emf* is induced in the coil which is given by

$$e = -\frac{d\lambda}{dt} = -N\frac{d\phi}{dt}\ V \tag{5.20}$$

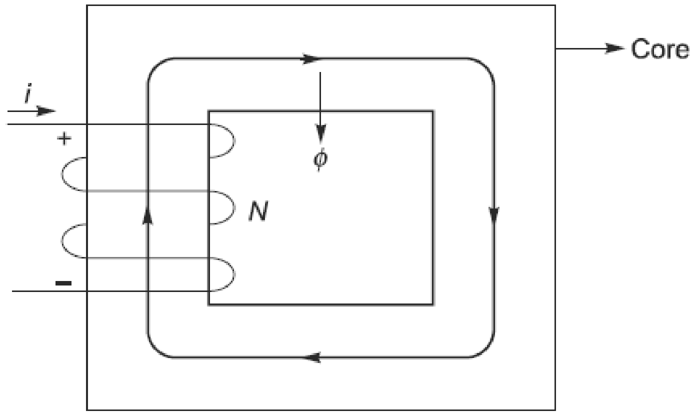


Fig. 5.13 *Flux ϕ passing through all N turns of a coil*

Electromagnetic Induction & Lenz's Law

2 Lenz's Law

The negative sign in Eq. (5.20) means that the induced *emf* would tend to cause a current flow in the coil, which would oppose the change in flux (the original cause of emf induction). This statement is known as Lenz's law.

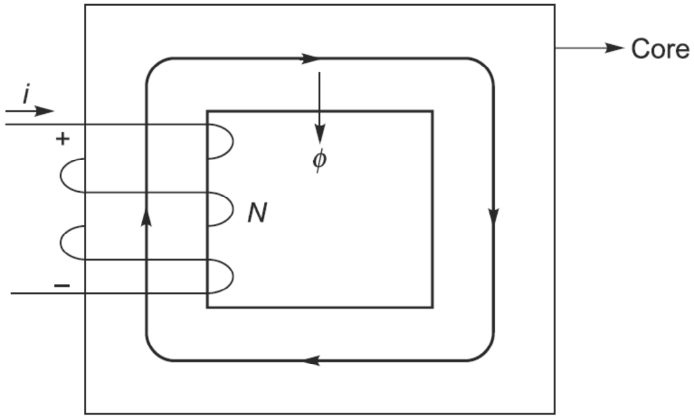


Fig. 5.13 *Flux ϕ passing through all N turns of a coil*

If the opposing polarity of emf is indicated on the coil terminals as in Fig. 5.13 then the Faraday's law need to give only the emf magnitude as

$$e = \frac{d\lambda}{dt} = N\frac{d\phi}{dt}\ V \qquad (5.21)$$

Electromagnetic Induction & Lenz's Law

Change in flux linkages of a coil may occur in two ways:

- The coil remains stationary and the flux through it changes with time. The emf so inducted is known as *statically induced emf* (*transformer emf*).
- Flux density distribution remains constant and stationary in space but the coil moves relative to it so as to change the flux linkages of the coil. The emf so inducted is known as *dynamically inducted emf* (*motional emf*).

Both the above processes of induction may occur simultaneously in a coil.

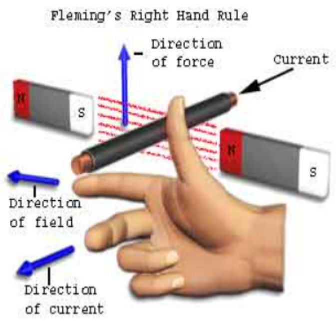
The dynamically induced emf in a conductor of length l(m) placed at angle θ to a stationary magnetic field of flux density B(T) cutting across it at speed v(m/s) is given by

$$e = |v \times B|\, l \text{ V}$$

$$= Blv \sin\theta \text{ V} \tag{5.22}$$

where θ is the angle between the direction of flux density and conductor velocity. In electric machines θ = 90°, so that

$$e = Blv \text{ V} \tag{5.23}$$



This is known as the *flux-cutting rule* with the direction of emf given by $v \times B$ or by the well-known *Fleming's right-hand rule*.

Extend the thumb, first and second fingers of the right hand mutually at right angles to each other. If the thumb represents the direction of v (motion of conductor with respect to B), first finger the direction of B then the second finger gives the direction of emf along l (the conductor).

Electromagnetic Induction & Lenz's Law

3 Lorentz Force Equation

Force of electromagnetic origin is given by

$$\mathbf{F} = l\,\mathbf{i} \times \mathbf{B} \ \ \mathrm{N} \tag{5.24}$$

where $\mathbf{F}$ is the force acting on a straight conductor of length l (m) carrying current i (A) placed in a uniform field of flux density B(T). The magnitude of force is given by

$$F = Bil \sin\theta \ \ \mathrm{N} \tag{5.25}$$

where direction is along $\mathbf{i} \times \mathbf{B}$ and θ is the angle between current direction and flux density. If $\theta = 90°$ as in electric machines

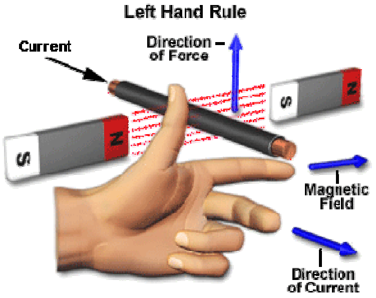
$$F = Bil \ \ \mathrm{N} \tag{5.26}$$

which is the well-known *Bil rule* or *Biot-Savart Law*.

The direction of force can also be found by the *Fleming's left-hand rule*.

Extend the thumb, first and second fingers of the left hand mutually at right angles to each other. If the thumb represents the direction of B, the second finger the direction of I then the first finger points in the direction of force on the conductor.

From Eq. (5.26), B can be imagined to have units of N/Am.



Working of Transformer

WORKING PRINCIPLE OF A TRANSFORMER

The basic principle of a transformer is electromagnetic induction.

A simple form of a transformer is shown in Figure 10.3(a). It essentially consists of two separate windings placed over the laminated silicon steel core. The winding to which AC supply connected is called primary winding and the winding to which load connected is called a secondary winding.

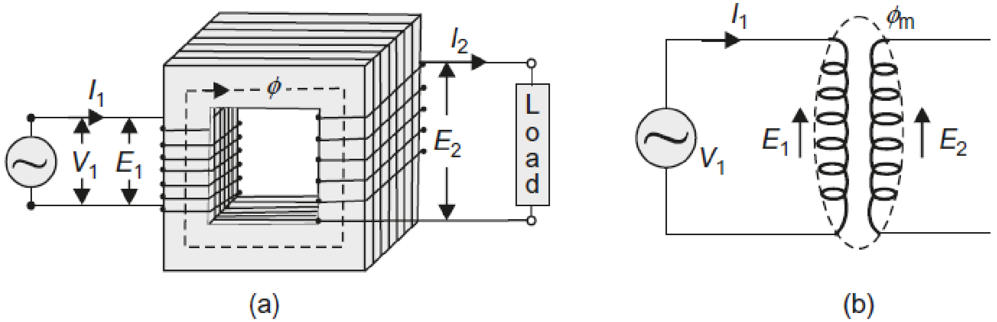


Fig. 10.3 **(a) Simple diagram of a transformer (b) Mutual flux linking with primary and secondary winding**

When AC supply of voltage V_1 is connected to primary winding, an alternating flux is set up in the core. This alternating flux when links with the secondary winding, an emf is induced in it called mutually induced emf. The direction of this induced emf is opposite to the applied voltage V_1, according to Lenz's law as shown in Figure 10.3(b).

The same alternating flux also links with the primary winding and produces self-induced emf E_1. This induced emf E_1 also acts in opposite direction to the applied voltage V_1 according to Lenz's law and hence called 'back emf'.

Working of Transformer

Although there is no electrical connection between primary and secondary winding, electrical power is transferred from primary circuit to secondary circuit through mutual flux.

The induced emf in the primary and secondary winding depends upon the rate of change of flux linkages, that is, $\left(N\dfrac{d\phi}{dt}\right)$. The rate of change of flux $(d\phi/dt)$ is the same for both primary and secondary windings. Therefore, an induced emf in primary winding is proportional to number of turns of the primary winding $(E_1 \propto N_1)$, and in secondary winding, it is proportional to number of turns of the secondary winding $(E_2 \propto N_2)$.

$\therefore$ In case $N_2 > N_1$, the transformer is step-up transformer, and when $N_2 < N_1$, the transformer is step-down transformer.

Turn ratio: The ratio of primary to secondary turns is called turn ratio, that is, turn ratio $= N_1/N_2$.

Transformation ratio: The ratio of secondary voltage to primary voltage is called voltage transformation ratio of the transformer. It is represented by K.

$$K = \frac{E_2}{E_1} = \frac{N_2}{N_1} (\text{since } E_2 \propto N_2 \text{ and } E_1 \propto N_1)$$

Working of Transformer

AN IDEAL TRANSFORMER

To understand the theory, operation, and applications of a transformer, it is better to view a transformer first as an ideal device. For this, the following assumptions are made:

1. Its coefficient of coupling (k) is unity.
2. Its primary and secondary windings are pure inductors having infinitely large value.
3. Its leakage flux and leakage inductances are zero.
4. Its self- and mutual inductances are zero having no reactance or resistance.
5. Its efficiency is 100 per cent having no loss due to resistance, hysteresis, or eddy current.
6. Its transformation ratio (or turn ratio) is equal to the ratio of its secondary to primary terminal voltage and also as the ratio of its primary to secondary current.
7. Its core has permeability (μ) of infinite value.

Thus, an ideal transformer is one which has no ohmic resistance and no magnetic leakage flux, that is, all the flux produced in the core links with both primary and secondary. Hence, transformer has no copper losses and core losses. It means an ideal transformer consists of two purely inductive coils wound on a loss-free core. Although in actual practice, it is impossible to realize such a transformer, yet for convenience, it is better to start with an ideal transformer and then extend it to an actual transformer.

In an ideal transformer, there is no power loss, and therefore, output must be equal to input.

Working of Transformer

That is, $E_2 I_2 \cos\phi = E_1 I_1 \cos\phi$ or $E_2 I_2 = E_1 I_2$ or $\dfrac{E_2}{E_1} = \dfrac{I_1}{I_2}$

Since, $E_2 \propto N_2; E_1 \propto N_1$ and $E_1 \cong V_1; E_2 \cong V_2$

$$\frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K(\text{transformation ratio})$$

Hence, primary and secondary currents are inversely proportional to their respective turns.

The ratio of secondary turns to primary turns is called transformation ratio of the transformer and is represented by K.

Behaviour and Phasor Diagram

Consider an ideal transformer whose secondary is open as shown in Figure 10.11(a). When its primary winding is connected to sinusoidal alternating voltage V_1, a current I_{mag} flows through it. Since the primary coil is purely inductive, the current I_{mag} lags behind the applied voltage V_1 by 90°. This current sets up alternating flux

Working of Transformer

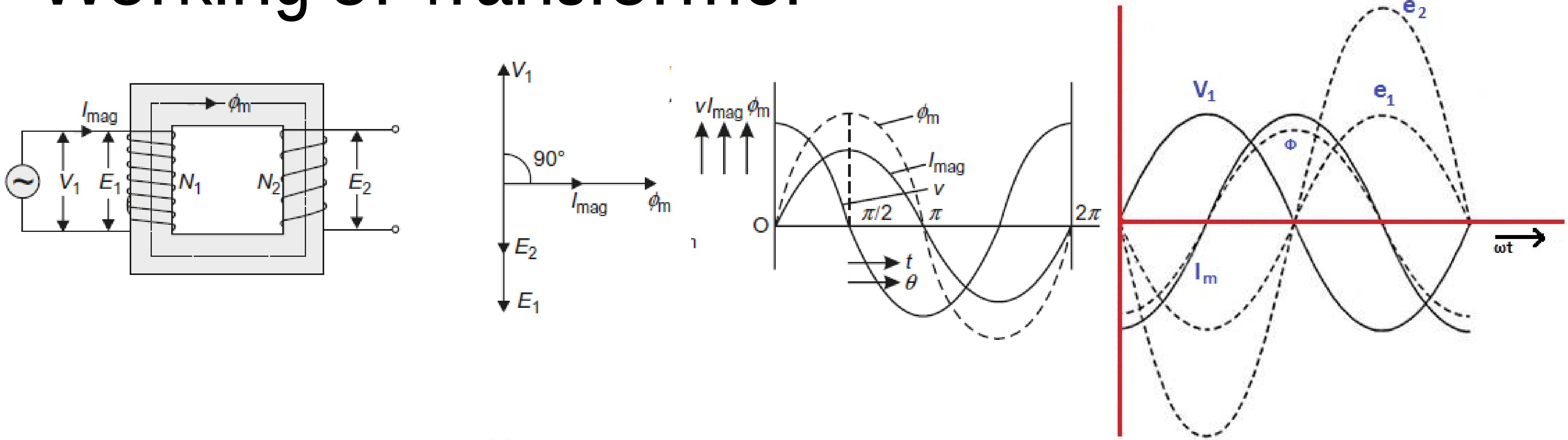


Fig. 10.11 **Ideal transformer (a) General view** **(b) Phasor diagram** **(c) Wave diagram**

(or mutual flux ϕ_m) in the core and magnetizes it. Hence, it is called magnetizing current. Flux is in phase with I_{mag} as shown in the phasor diagram and wave diagram in Figure 10.11(b) and (c), respectively. The alternating flux links with both primary and secondary windings. When it links with primary, it produces self-induced emf E_1 in opposite direction to that of applied voltage V_1. When it links with secondary winding, it produces mutually induced emf E_2 in opposite direction to that of applied voltage. Both the emfs E_1 and E_2 are shown in phasor diagram (Fig. 10.11(b)).

Working of Transformer

TRANSFORMER ON DC

A transformer cannot work on DC supply. If a rated DC voltage is applied across the primary, a flux of constant magnitude will be set up in the core. Hence, there will not be any self-induced emf (which is only possible with the rate of change of flux linkages) in the primary winding to oppose the applied voltage. As the resistance of the primary winding is very low, the primary current will be quite high as given by the Ohm's law.

$$\text{Primary current} = \frac{\text{DC applied voltage}}{\text{Resistance of primary winding}}$$

This current is much more than the rated full-load current of primary winding. Thus, it will produce lot of heat (I^2R) loss and burns the insulation of the primary winding, and consequently, the transformer will be damaged. Hence, DC is never applied to a transformer.

Working of Transformer

EMF EQUATION

When sinusoidal voltage is applied to the primary winding of a transformer, a sinusoidal flux, as shown in Figure 10.12 is set up in the iron core which links with primary and secondary winding.

Let ϕ_m = Maximum value of flux in Wb

f = supply frequency in Hz (or c/s)

N_1 = No. of turns in primary

N_2 = No. of turns in secondary

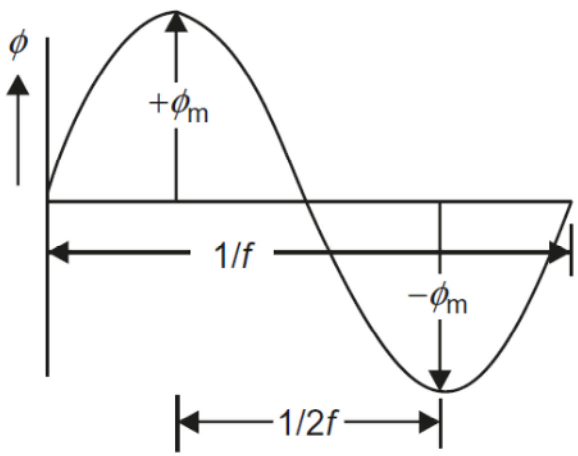


Fig. 10.12 Wave diagram of mutual flux set-up in magnetic core

As shown in Figure 10.19, flux changes from $+\phi_m$ to $-\phi_m$ in half cycle, that is, $\frac{1}{2f}$ second,

Average rate of change of flux

$$= \frac{\phi_m - (-\phi_m)}{1/2f} = 4f\,\phi_m \text{ Wb/s}$$

Now, the rate of change of flux per turn is the average induced emf per turn in volt.

$\therefore$ Average emf induced per turn = $4f\,\phi_m$ \volt

Working of Transformer

For a sinusoidal wave,

$$\frac{\text{RMS value}}{\text{Average value}} = \text{Form factor} = 1.11$$

$\therefore$ RMS value of emf induced/turn, $E = 1.11 \times 4f\phi_m = 4.44f\phi_m$ volt

Since primary and secondary have N_1 and N_2 turns, respectively.

$\therefore$ RMS value of emf induced in primary,

$$E_1 = (\text{emf induced/turn}) \times \text{No. of primary turns}$$

$$= 4.44N_1 f \phi_m \text{volt} \qquad (10.1)$$

Similarly, rms value of emf induced in secondary,

$$E_2 = 4.44N_2 f \phi_m \text{volt} \qquad (10.2)$$

From eq. (10.1), we get, $$\frac{E_1}{N_1} = 4.44f\phi_m \text{ volt/turn} \qquad (10.3)$$

From eq. (10.1), we get, $$\frac{E_2}{N_2} = 4.44f\phi_m \text{ volt/turn} \qquad (10.4)$$

Working of Transformer

Equations (10.3) and (10.4) clearly show that emf induced per turn on both the sides, that is, primary and secondary is the same.

Again, we can find the voltage ratio,

$$\frac{E_2}{E_1} = \frac{4.44 N_2 f \phi_m}{4.44 N_1 f \phi_m} \quad \text{or} \quad \frac{E_2}{E_1} = \frac{N_2}{N_1} = K \text{ (transformation ratio)}$$

Equations (10.1) and (10.2) can be written in the form of maximum flux density B_m using relation,

$$\phi_m = B_m \times A_i \text{ (where } A_i \text{ is iron area)}$$

$$\therefore \qquad E_1 = 4.44 N_1 f B_m A_i \text{ volts} \quad \text{and} \quad E_2 = 4.44 N_2 f B_m A_i \text{ volt}$$

Working of Transformer

Example

A 25 kVA transformer has 500 turns on the primary and 40 turns on the secondary winding. The primary is connected to 3000 V, 50 Hz mains, calculate (i) primary and secondary currents at full load, (ii) the secondary emf, and (iii) the maximum flux in the core. Neglect magnetic leakage, resistance of the winding and the primary no-load current in relation to the full-load current.

Solution:

(i) At full load, $I_1 = \dfrac{25 \times 10^3}{3000} = 8.33$

Now, $\dfrac{I_1}{I_2} = \dfrac{E_2}{E_1} = \dfrac{N_2}{N_1}$

Secondary current, $I_2 = \dfrac{N_1}{N_2} \times I_1 = \dfrac{500}{40} \times 8.33 = 104.15 \text{ A}$

(ii) Secondary emf. $E_2 = \dfrac{N_2}{N_1} \times E_1 = \dfrac{40}{500} \times 3000 = 240 \text{ V}$

(iii) Using relation, $E_1 = 4.44 \times N_1 \times f \times \phi_m$

$$3300 = 4.44 \times 500 \times 50 x \phi_m$$

or $\phi_m = \dfrac{3000}{4.44 \times 500 \times 50} = 27 \text{ m Wb}$

Working of Transformer

Example

A 100 kVA, 3300/200 V, 50 Hz single-phase transformer has 40 turns on the secondary, calculate (i) the values of primary and secondary currents, (ii) the number of primary turns, and (iii) the maximum value of the flux. If the transformer is to be used on a 25 Hz system, calculate (iv) the primary voltage, assuming that the flux is increased by 10 per cent and (v) the kVA rating of the transformer assuming the current density in the windings to be unaltered.

Solution:

(i) Full-load primary current, $I_1 = \dfrac{100 \times 1000}{3300} = 30.3$ A

Full-load secondary current, $I_2 = \dfrac{100 \times 1000}{200} = 500$ A

(ii) No. of primary turns, $N_1 = N_2 \times \dfrac{E_1}{E_2} = 40 \times \dfrac{3300}{200} = 660$

(iii) We know, $E_2 = 4.44 \times f \times \phi_{max} \times N_2$ V

$$200 = 4.44 \times 50 \times \phi_{max} \times 40$$

$$\therefore \quad \phi_{max} = \frac{200}{4.44 \times 50 \times 40} = 0.0225 \text{ Wb}$$

Working of Transformer

(iv) As the flux is increased by 10% at 25 Hz

$\therefore$ Flux at 25 Hz, $\phi'_m = 0.0225 \times 1.1 = 0.02475$ Wb

$\therefore$ Primary voltage $= 4.44 \times N_1 \times f' \times \phi'_m$ volt

$= 4.44 \times 660 \times 25 \times 0.02475 = 1815$ V

(v) For the same current density, the full-load primary and secondary currents remain unaltered.

$$\therefore \text{ kVA rating of the transformer} = \frac{30.3 \times 1815}{1000} = 55 \text{ kVA}$$