BASIC ELECTRICAL ENGINEERING

COURSE FILE

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GEETHANJALI COLLEGE OF ENGINEERING AND TECHNOLOGY(AUTONOMOUS)

Department Of Electrical and Electronics Engineering

Name of the Subject: BASIC ELECTRICAL ENGINEERING

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2. SYLLABUS

20EE11001– BASIC ELECTRICAL ENGINEERING

Course Objectives: Develop ability to

- understand the concepts of DC circuits and its analysis.
- understand the concepts of AC single phase circuits and its analysis.
- understand the concepts of single phase and three phase Transformers.
- understand the concepts of AC and DC machines.
- understand the working of various domestic electrical installation components.

Course Outcomes: At the end of the course, student would be able to

- analyze and solve DC electrical circuits using Circuit laws and theorems.
- analyze and solve AC electrical circuits.
- know the construction, operation of AC and DC Machines
- analyze the characteristics of DC and AC machines.
- differentiate various domestic electrical installation components.

UNIT-I: D.C. Circuits Electrical circuit elements (R, L and C), voltage and current sources, KVL&KCL, analysis of simple circuits with dc excitation. Superposition, Thevenin and Norton Theorems. Time-domain analysis of first-order RL and RC circuits.

UNIT-II: A.C. Circuits Representation of sinusoidal waveforms, peak and rms values, phasor representation, real power, reactive power, apparent power, power factor, Analysis of single-phase ac circuits consisting of R, L, C, RL, RC, RLC combinations (series and parallel), resonance in series RL-C circuit.

UNIT-III: Faradays Laws of Electromagnetic Induction. Statically and dynamically induced emf. Transformers: Ideal and practical transformers, equivalent circuit, losses in transformers and efficiency. Auto-transformer and Three-phase transformer connections, voltage and current relation.

UNIT-IV: Direct-Current Machines: Construction, operation and Types. Torque-Speed Characteristics of DC shunt and series motors and its applications. Generation of rotating magnetic fields, Construction and working of a three-phase induction motor, Significance of torque-slip characteristic. Single-phase induction motor: Construction and working and its applications.

UNIT-V: Electrical Installations: Components of LT Switchgear: Switch Fuse Unit (SFU), MCB, ELCB, MCCB, Types of Wires and Cables, Earthing. Types of Batteries, Important Characteristics for Batteries and their applications. Elementary calculations for energy consumption.

Text-Books:

1. Basic Electrical Engineering - D.P. Kothari and I.J. Nagrath, 3rd edition 2010, Tata McGraw Hill.
2. Electrical Engineering Fundamentals, Vincent Del Toro, Second Edition, Prentice Hall India, Pvt. Ltd.

3. VISION OF THE DEPARTMENT

To impart quality technical education in Electronics and Communication Engineering emphasizing analysis, design/synthesis and evaluation of hardware/ embedded software, using various Electronic Design Automation (EDA) tools with accent on creativity, innovation and research thereby producing competent engineers who can meet global challenges with societal commitment.

4. MISSION OF THE DEPARTMENT

1. To impart quality education in fundamentals of basic sciences, mathematics, electronics and communication engineering through innovative teaching-learning processes.
2. To facilitate Graduates define, design, and solve engineering problems in the field of Electronics and Communication Engineering using various Electronic Design Automation (EDA) tools.
3. To encourage research culture among faculty and students thereby facilitating them to be creative and innovative through constant interaction with R & D organizations and Industry.
4. To inculcate teamwork, imbibe leadership qualities, professional ethics and social responsibilities in students and faculty.

1. PROGRAM EDUCATIONAL OBJECTIVES:

2. To prepare students with excellent comprehension of basic sciences, mathematics and engineering subjects facilitating them to gain employment or pursue postgraduate studies with an appreciation for lifelong learning.
3. To train students with problem solving capabilities such as analysis and design with adequate practical skills that are Program Specific wherein they demonstrate creativity and innovation that would enable them to develop state of the art equipment and technologies of multidisciplinary nature for societal development.
4. To inculcate positive attitude, professional ethics, effective communication and interpersonal skills which would facilitate them to succeed in the chosen profession exhibiting creativity and innovation through research and development both as team member and as well as leader.

PROGRAM OUTCOMES (POs)

1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
2. **Problem analysis**: Identify, formulate, research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
8. **Ethics:** Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
9. **Individual and team work**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one’s own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.
12. **Life-long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOMES (PSOs)

1. An ability to design an Electronics and Communication Engineering system, component, or process and conduct experiments, analyze, interpret data and prepare a report with conclusions to meet desired needs within the realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability.
2. An ability to use modern Electronic Design Automation (EDA) tools, software and electronic equipment to analyze, synthesize and evaluate Electronics and Communication Engineering systems for multidisciplinary tasks.

5. COURSE OBJECTIVES

Course Objectives: Develop ability to

- understand the concepts of DC circuits and its analysis.
- understand the concepts of AC single phase circuits and its analysis.
- understand the concepts of single phase and three phase Transformers.
- understand the concepts of AC and DC machines.
- understand the working of various domestic electrical installation components.

COURSE OUTCOMES (COS)

Course Outcomes: At the end of the course, student would be able to

CO1. analyze and solve DC electrical circuits using Circuit laws and theorems.
CO2. analyze and solve AC electrical circuits.
CO3. know the construction, operation of AC and DC Machines
CO4. analyze the characteristics of DC and AC machines.
CO5. differentiate various domestic electrical installation components.

6. BRIEF NOTES ON THE IMPORTANCE OF THE COURSE AND HOW IT FITS INTO THE CURRICULUM:-

a. What role does this course play within the Program?

- Electrical Engineering forms the foundation of Electrical, Electronics, Communication, Controls, **Computers, Information,** Instrumentation etc. Hence a good grasp of the fundamentals of Electrical Engineering is an absolute necessity to become a good Engineer in any Discipline.
- This course strengthens the basic knowledge of the students which is related to electrical engineering field.
- This is a basic course which helps in understanding the basic elements like Resistors, Inductors, Capacitors, Voltage source, Current source, Electrical Power, Electrical Energy etc., which are useful in Electrical Engineering Field.
- This is a basic course which helps the students in understanding the basic Knowledge about DC Machines, AC Machines, Transformers, Electrical Measuring Instruments like voltmeter, ammeter, wattmeters etc., which are useful in Electrical Engineering Field.

b. How is the course unique or different from other courses of the Program?

- This is the only course where the students can learn the basic concepts of Ohm’s law, KVL & KCL, Basic Network Theorems, Basic Knowledge on Electrical Machines, Transformers and Electrical Measuring Instruments.

c. **What essential knowledge or skills should they gain from this experience?**

- Students gain essential knowledge in problem solving and Decision making skills when they face basic problems in Electrical Field.

d. **Why is this course important for students to take?**

- This course important for studentsin order to understand the basic concepts of electrical engineering

e. What is/are the prerequisite(s) for this course?

- Engineering Physics and Engineering Mathematics.

f. When students complete this course, what do they need know or be able to do?

- Able to design, analyze and evaluate the Electrical circuits.
- Able to analyze and operate the Electrical machines.

g. Is there specific knowledge that the students will need to know in the future?

- In future, students have to apply these concepts in the design of Electrical circuits and to operate the Electrical machines in Power Industry.

h. **Are there certain practical or professional skills that students will need to apply in the future?**

- YES. Most of the mini and major projects are generally based small range of Electrical Instruments, motors and Transformers.

i. Five years from now, what do you hope students will remember from this course?

- This knowledge is useful to them to solve basic problems when they face in future.

j. **What is it about this course that makes it unique or special?**

- It is the only fundamental course that facilitates students in the attainment of all levels of basic Knowledge in Electrical Field.

k. Why does the program offer this course?

- This is the basic course in Electrical field. Without this course, students cannot take decisions when they face basic problems in Electrical field.

l. What is the value of taking this course? How exactly does it enrich the program?

- This course plays a vital role in design and development of Electrical circuits in the discipline of Electrical Engineering which is so essential and useful to the development of society and this course also helps for the student's professional career growth in terms of professional career.
- This course makes significant contributions to the following program outcomes:
    - An ability to apply knowledge of mathematics, science, and engineering.
    - An ability to design and conduct experiments, as well as to analyze Electrical Circuits and Electrical Machines.
    - an ability to identify, formulate, and solve engineering problems, an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

7. PREREQUISITES:

NONE

8. INSTRUCTIONAL LEARNING OUTCOMES:-

Unit 1

1. Ability to learn basic circuit components, Ohm's law, Kirchhoff's laws.
2. Ability to learn types of elements, types of sources.
3. Ability to analyze resistive networks, inductive networks, capacitive networks,
4. Ability to learn Network theorems
5. Ability to solve problems on Network theorems

Unit 2

1. Ability to learn fundamentals of Alternating Current (AC).
2. Ability to Calculate RMS and Average values of alternating currents and voltage
3. Ability to find form factor and peak factor.
4. Ability to represent alternating quantities in phasor form.
5. Ability to analyze AC circuits with single basic network element, single phase series circuits.

Unit 3

1. Ability to know the Principles of operation, constructional details of Transformer.
2. Ability to learn EMF equation of a Transformer.
3. Ability to find the losses in a transformer.
4. Ability to find efficiency of a Transformer.

Unit 4

1. Ability to know Construction and working of a three-phase induction motor
2. Ability to know the Principles of operation Three phase induction motor.
3. Ability to know the working, torque-speed characteristic of DC Machines.

Unit 5

1. Ability to understand Components of LT Switchgear: Switch Fuse Unit (SFU), MCB, ELCB, MCCB
2. Ability to understand Types of Wires and Cables, Earthling. Types of Batteries.
3. Ability to understand the energy consumption and their calculations

9. COURSE MAPPING WITH PO'S

Mapping of Course Outcomes with Programme Outcomes:

POs→ **COs↓**	1	2	3	4	5	6	7	8	9	10	11	12
CO1: To analyze and solve DC electrical circuits using network laws and theorems.	3	3	**3**			3		3	3	3		3
CO2:To analyze and solve AC electrical circuits using network principles	3	3	**3**			3		3	3	3		3
CO3: To understand and analyze basic Electric and Magnetic circuits	3	3	**3**			3		3	3	3		3
CO4: To study the working principles of Electrical Machines.	3	3	**3**			3		3	3	3		3
CO5: To introduce components of Low Voltage Electrical Installations	3	3	**3**			3		3	3	3		3

3-high

2-medium

1-low

10. CLASS TIME TABLES:

To be attached

11. INDIVIDUAL TIMETABLES:

To be attached

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12. LESSON PLAN/METHODOLOGY

S.No.	Unit No	Topic Covered	No of Periods	Teaching Aids
1.	UNIT-1	Introduction to Electrical Engineering	1	BB
2.		Voltage, Current, EMF	1	BB
3.		Basic Circuit components R,L,C	1	BB
4.		Ohm's Law	1	BB
5.		Kirchhoff's Laws (KCL)	1	BB
6.		Kirchhoff's Laws (KVL)	1	BB
7.		Voltage And Current Sources	1	BB
8.		Analysis of simple circuits with dc excitation	2	BB
9.		Network Theorems Superposition Theorem	2	BB
10.		Thevenin's Theorem	1	BB
11.		Norton's thoerem	1	BB
12.		Time response analysis of first order RL and RC circuits	2	BB
13.		Simple Problems	1	BB
14.		Revision	1	BB
15.	UNIT-2	Alternating Quantities	1	BB
16.		Principle of ac voltages, waveforms and basic definitions	1	BB
17.		Root Mean Square and average values of alternatingCurrents and voltages	1	BB
18.		Form Factor and Peak Factor	1	BB
19.		Phasor Representation of Alternating Quantities	1	BB
20.		Real,reactive and apparent power	1	BB
21.		Analysis of AC circuits with single basic network element R,L ,C	1	BB
22.		Resonance in Series R-L-C Circuits	2	BB
23.		Formulas related to RLC	1	BB
24.		Problems	1	BB
25.		Revision	1	BB
26.	UNIT-3	Transformers: Principle of operation, Types of transformers	2	OHP, BB
27.		Construction Features	1	BB,OHP
28.		Phasor Diagram on Load and No Load	1	BB
29.		Performance of Transformers: Losses and Efficiency of transformers.	1	BB
30.		Equivalent circuit	1	BB
31.		Autotransformers	1	OHP
32.		Three phase connections	1	OHP, BB
33.		Revision	1	BB
34.	UNIT-4	Generation of rotating magnetic fields	1	BB
35.		Construction and working of a three-phase induction motor.	2	BB,OHP

36.		Significance of torque-slip characteristic	1	BB
37.		Loss components and efficiency	1	BB
38.		Problems	1	BB
39.		Principle of Operation of DC machines	1	BB
40.		classification	1	BB
41.		Construction of DC Machine	1	BB,OHP
42.		Working Principle of DC Machine	1	BB
43.		Torque-speed characteristic of separately excited dc motor.	1	BB
44.		Single-phase induction motor.	1	BB
45.		**operation**	1	BB
46.		problems	1	BB
47.		Numerical	1	BB
48.		Revision	1	BB
49.	**UNIT-5**	Introduction to Electrical InstallationsImportant	1	BB
50.		Components of LT Switchgear: Switch Fuse Unit (SFU), MCB, ELCB, MCCB,	1	BB
51.		Types of Wires	1	BB
52.		Types of Batteries	1	BB
53.		Types of Cables	1	BB
54.		Earthing	1	BB
55.		Characteristics for Batteries.	1	BB
56.		Elementary calculations for energy consumption,	1	BB
57		Revision class unit 5	1	BB
58		Solve University questions	1	BB
59		Solve University questions	1	BB

12. <u>DETAILED NOTES</u>

UNIT-I

Introduction to Electrical Engineering:

In practice, the electrical circuits may consist of one or more sources of energy and number of electrical parameters, connected in different ways. The different electrical parameters or elements are resistors, capacitors and inductors. The combination of such elements alongwith various sources of energy gives rise to complicated electrical circuits, generally referred as **networks**. The terms **circuit** and **network** are used synonymously in the electrical literature. The d.c. circuits consist of only resistances and d.c. sources of energy. And the circuit analysis means to find a current through or voltage across any branch of the circuit. This chapter incıudes various techniques of analysing d.c. circuits.

The chapter explains the basic terminology used in the network analysis and classification of networks. It explains Ohm's law, Kirchhoff's laws and various network simplification techniques such ∴ series-parallel combinations, star-delta transformation, source transformation etc. These techniques are very basic and useful, which can be further applied to understa 1 various network theorems. The network theorems such as Superposition, Thevenin's, Norton's and Maximum power transfer as applied to d.c. circuits are also included in this chapter.

2.5 Ohm's Law

This law gives relationship between the potential difference (V), the current (I) and the resistance (R) of a d.c. circuit. **Dr. Ohm** in 1827 discovered a law called **Ohm's Law.** It states,

Ohm's Law : *The current flowing through the electric circuit is directly proportional to the potential difference across the circuit and inversely proportional to the resistance of the circuit, provided the temperature remains constant.*

Mathematically, $\boxed{I \propto \dfrac{V}{R}}$

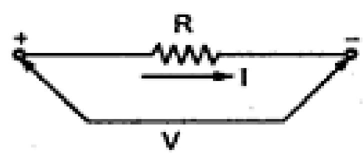


Fig. 2.11 Ohm's law

Where I is the current flowing in amperes, the V is the voltage applied and R is the resistance of the conductor, as shown in the Fig. 2.11.

Now $I = \dfrac{V}{R}$

The unit of potential difference is defined in such a way that the constant of proportionality is unity.

Ohm's Law is,	$I = \dfrac{V}{R}$	amperes
	$V = I R$	volts
	$\dfrac{V}{I} =$ constant $= R$	ohms

The Ohm's law can be defined as,

The ratio of potential difference (V) between any two points of a conductor to the current (I) flowing between them is constant, provided that the temperature of the conductor remains constant.

Key Point: *Ohm's Law can be applied either to the entire circuit or to the part of a circuit. If it is applied to entire circuit, the voltage across the entire circuit and resistance of the entire circuit should be taken into account. If the Ohm's Law is applied to the part of a circuit, then the resistance of that part and potential across that part should be used.*

2.14.1 Kirchhoff's Current Law (KCL)

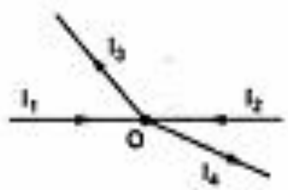


Fig. 2.33 Junction point

Consider a junction point in a complex network as shown in the Fig. 2.33.

At this junction point if $I_1 = 2A$, $I_2 = 4A$ and $I_3 = 1A$ then to determine I_4 we write, total current entering is $2 + 4 = 6A$ while total current leaving is $1 + I_4$ A

And hence, $I_4 = 5$ A.

This analysis of currents entering and leaving is nothing but the application of Kirchhoff's Current Law. The law can be stated as,

The total current flowing towards a junction point is equal to the total current flowing away from that junction point.

Another way to state the law is,

The algebraic sum of all the current meeting at a junction point is always zero.

The word algebraic means considering the signs of various currents.

$$\boxed{\sum I \text{ at junction point} = 0}$$

Sign convention : Currents flowing towards a junction point are assumed to be positive while currents flowing away from a junction point assumed to be negative.

e.g. Refer to Fig. 2.33, currents I_1 and I_2 are positive while I_3 and I_4 are negative.

Applying KCL, $\sum I$ at junction O $= 0$

$$I_1 + I_2 - I_3 - I_4 = 0 \text{ i.e. } I_1 + I_2 = I_3 + I_4$$

The law is very helpful in network simplification.

2.14.2 Kirchhoff's Voltage Law (KVL)

"In any network, the algebraic sum of the voltage drops across the circuit elements of any closed path (or loop or mesh) is equal to the algebraic sum of the e.m.f s in the path"

In other words, "the algebraic sum of all the branch voltages, around any closed path or closed loop is always zero."

$$\boxed{\text{Around a closed path } \sum V = 0}$$

The law states that if one starts at a certain point of a closed path and goes on tracing and noting all the potential changes (either drops or rises), in any one particular direction, till the starting point is reached again, he must be at the same potential with which he started tracing a closed path.

Sum of all the potential rises must be equal to sum of all the potential drops while tracing any closed path of the circuit. The total change in potential along a closed path is always zero.

This law is very useful in loop analysis of the network.

2.14.5 Steps to Apply Kirchhoff's Laws to Get Network Equations

The steps are stated based on the branch current method.

Step 1 : Draw the circuit diagram from the given information and insert all the values of sources with appropriate polarities and all the resistances.

Step 2 : Mark all the branch curretns with some assumed directions using KCL at various nodes and junction points. Kept the number of unknown currents minimum as far as possible to limit the mathematical calculations required to solve them later on.

Assumed directions may be wrong, in such case answer of such current will be mathematically negative which indicates the correct direction of the current. A particular current leaving a particular source has some magnitude, then same magnitude of current should enter that source after travelling through various branches of the network.

Step 3 : Mark all the polarities of voltage drops and rises as per directions of the assumed branch currents flowing through various branch resistances of the network. This is necessary for application of KVL to various closed loops.

Step 4 : Apply KVL to different closed paths in the network and obtain the corresponding equations. Each equation must contain some element which is not considered in any previous equation.

> **Key Point** : *KVL must be applied to sufficient number of loops such that each element of the network is included at least once in any of the equations.*

Step 5 : Solve the simultaneous equations for the unknown currents. From these currents unknown voltages and power consumption in different resistances can be calculated.

What to do if current source exists ?

> **Key Point :** *If there is current source in the network then complete the current distribution considering the current source. But while applying KVL, the loops should not be considered involving current source. The loop equations must be written to those loops which do not include any current source. This is because drop across current source is unknown.*

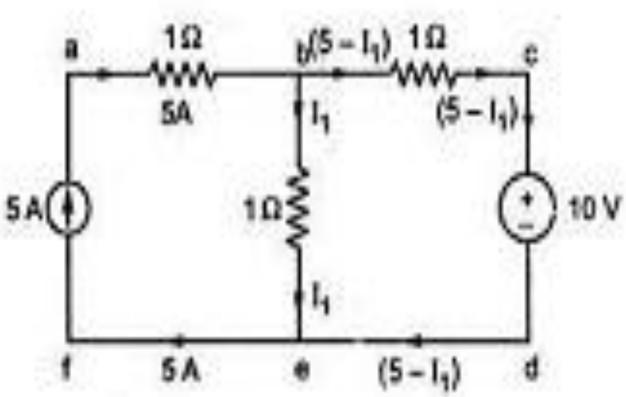


Fig. 2.36

For example, consider the circuit shown in the Fig. 2.36. The current distribution is completed interms of current source value. Then KVL must be applied to the loop bcdeb, which does not include current source. The loop **abefa should not be used for KVL application,** as it includes current source. Its effect is already considered at the time of current distribution.

Network:

Any arrangement of the various electrical energy sources along with the different circuit elements is called an **electrical network.** Such a network is shown in the Fig. 2.1.

Network Element

Any individual circuit element with two terminals which can be connected to other circuit element, is called a **network element.**

Network elements can be either active elements or passive elements. Active elements are the elements which supply power or energy to the network. Voltage source and

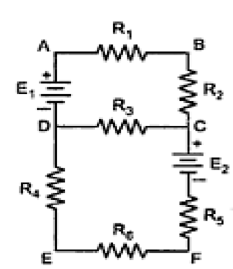


Fig. 2.1 An electrical network

current source are the examples of active elements. Passive elements are the elements which either store energy or dissipate energy in the form of heat. Resistor, inductor and capacitor are the three basic passive elements. Inductors and capacitors can store energy and resistors dissipate energy in the form of heat.

Node:

A point at which two or more elements are joined together is called **node.** The junction points are also the nodes of the network. In the network shown in the Fig. 2.1, A, B, C, D, E and F are the nodes of the network.

2.3 Classification of Electrical Networks

The behaviour of the entire network depends on the behaviour and characteristics of its elements. Based on such characteristics electrical network can be classified as below :

i) Linear Network : A circuit or network whose parameters i.e. elements like resistances, inductances and capacitances are always constant irrespective of the change in time, voltage, temperature etc. is known as **linear network.** The Ohm's law can be applied to such network. The mathematical equations of such network can be obtained by using the law of superposition. The response of the various network elements is linear with respect to the excitation applied to them.

ii) Non linear Network : A circuit whose parameters change their values with change in time, temperature, voltage etc. is known as **non linear network** . The Ohm's law may not be applied to such network. Such network does not follow the law of superposition. The response of the various elements is not linear with respect to their excitation. The best example is a circuit consisting of a diode where diode current does not vary linearly with the voltage applied to it.

iii) Bilateral Network : A circuit whose characteristics, behaviour is same irrespective of the direction of current through various elements of it, is called **bilateral network.** Network consisting only resistances is good example of bilateral network.

iv) Unilateral Network : A circuit whose operation, behaviour is dependent on the direction of the current through various elements is called **unilateral network.** Circuit consisting diodes, which allows flow of current only in one direction is good example of unilateral circuit.

v) Active Network : A circuit which contains at least one source of energy is called **active.** An energy source may be a voltage or current source.

vi) Passive Network : A circuit which contains no energy source is called **passive circuit.** This is shown in the Fig. 2.2.

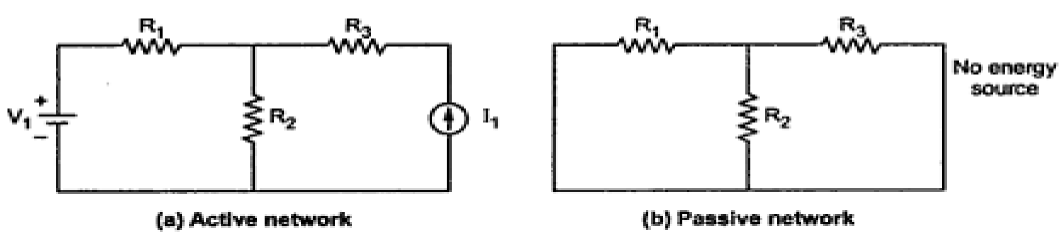


Fig. 2.2

vii) Lumped Network : A network in which all the network elements are physically separable is known as **lumped network.** Most of the electric networks are lumped in nature, which consists elements like R, L, C, voltage source etc.

viii) Distributed Network : A network in which the circuit elements like resistance, inductance etc. cannot be physically separable for analysis purposes, is called **distributed network.** The best example of such a network is a transmission line where resistance, inductance and capacitance of a transmission line are distributed all along its length and cannot be shown as a separate elements, any where in the circuit.

The classification of networks can be shown as,

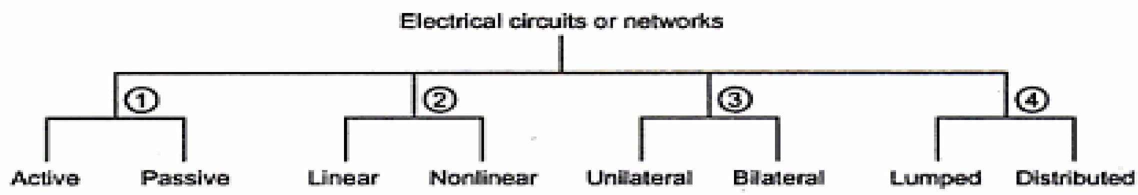


Fig. 2.3 Classification of networks

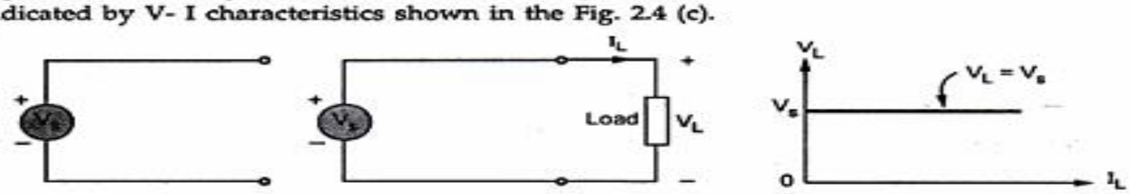
2.4 Energy Sources

There are basically two types of energy sources ; voltage source and current source. These are classified as i) Ideal source and ii) Practical source.

Let us see the difference between ideal and practical sources.

2.4.1 Voltage Source

Ideal voltage source is defined as the energy source which gives constant voltage across its terminals irrespective of the current drawn through its terminals. The symbol for ideal voltage source is shown in the Fig. 2.4 (a). This is connected to the load as shown in Fig. 2.4 (b). At any time the value of voltage at load terminals remains same. This is indicated by V- I characteristics shown in the Fig. 2.4 (c).

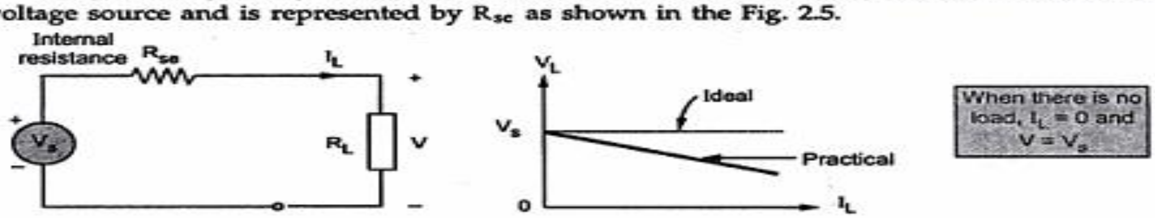


(a) Symbol (b) Circuit (c) Characteristics

Fig. 2.4 Ideal voltage source

Practical voltage source :

But practically, every voltage source has small internal resistance shown in series with voltage source and is represented by R_{se} as shown in the Fig. 2.5.



(a) Circuit (b) Characteristics

Fig. 2.5 Practical voltage source

Because of the R_{se}, voltage across terminals decreases slightly with increase in current and it is given by expression,

$$\boxed{V_L = -(R_{se}) I_L + V_S = V_S - I_L R_{se}}$$

Key Point: *For ideal voltage source, $R_{se} = 0$*

Voltage sources are further classified as follows,

i) Time Invariant Sources :

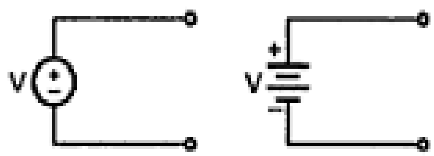


Fig. 2.6 (a) D. C. source

The sources in which voltage is not varying with time are known as time **invariant voltage sources** or **D.C. sources**. These are denoted by capital letters. Such a source is represented in the Fig. 2.6 (a).

ii) Time Variant Sources :

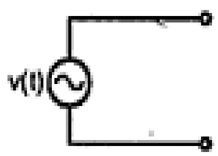


Fig. 2.6 (b) A. C. source

The sources in which voltage is varying with time are known as time **variant voltage sources or A.C. sources**. These are denoted by small letters. This is shown in the Fig. 2.6 (b).

2.4.2 Current Source

Ideal current source is the source which gives constant current at its terminals irrespective of the voltage appearing across its terminals. The symbol for ideal current source is shown in the Fig. 2.7 (a). This is connected to the load as shown in the Fig. 2.7 (b). At any time, the value of the current flowing through load I_L is same i.e. is irrespective of voltage appearing across its terminals. This is explained by V-I characteristics shown in the Fig. 2.7 (c).

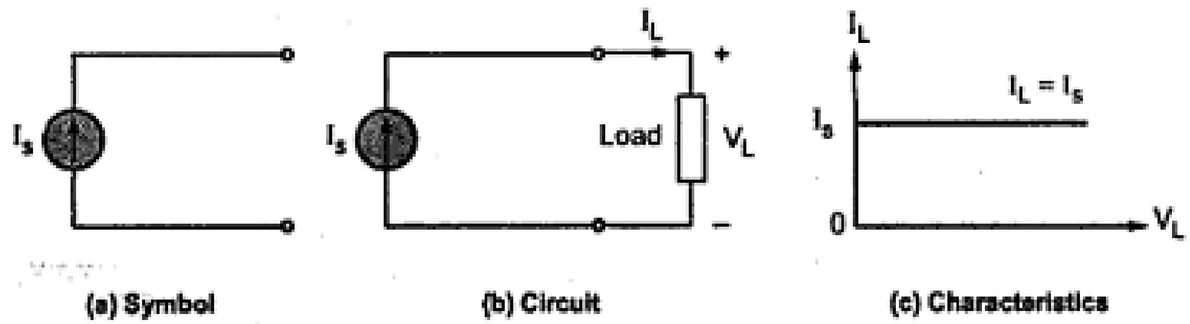


Fig. 2.7 Ideal current source

But practically, every current source has high internal resistance, shown in parallel with current source and it is represented by R_{sh}. This is shown in the Fig. 2.8.

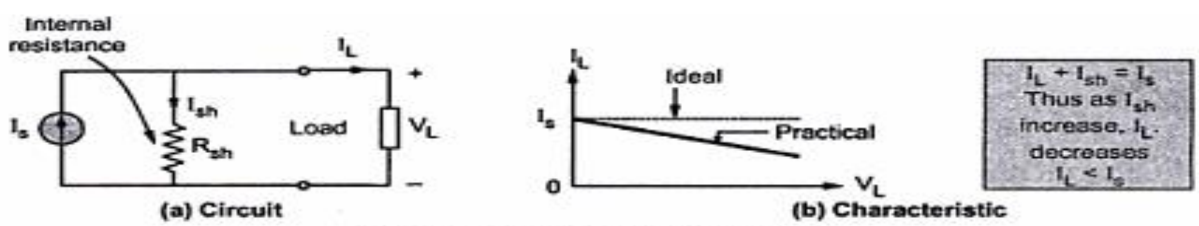


Fig. 2.8 Practical current source

Because of R_{sh}, current through its terminals decreases slightly with increase in voltage at its terminals.

Similar to voltage sources, current sources are classified as follows :

i) Time Invariant Sources :

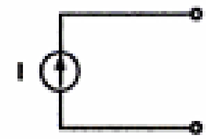


Fig. 2.9 (a) D. C. source

The sources in which current is not varying with time are known as **time invarient current sources** or **D.C. sources.** These are denoted by capital letters.

Such a current source is represented in the Fig. 2.9 (a).

ii) Time Variant Sources :

The sources in which current is varying with time are known as **time variant current sources** or **A.C. sources.** These are denoted by small letters.

Such a source is represented in the Fig. 2.9 (b).

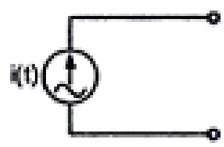


Fig. 2.9 (b) A. C. source

The sources which are discussed above are independent sources because these sources does not depend on other voltages or currents in the network for their value. These are represented by a circle with a polarity of voltage or direction of current indicated inside

2.4.3 Dependent Sources

Dependent sources are those whose value of source depends on voltage or current in the circuit. Such sources are indicated by diamond as shown in the Fig. 2.10 and further classified as,

i) Voltage Dependent Voltage Source : It produces a voltage as a function of voltages elsewhere in the given circuit. This is called **VDVS.** It is shown in the Fig. 2.10 (a).

ii) Current Dependent Current Source : It produces a current as a function of currents elsewhere in the given circuit. This is called **CDCS.** It is shown in the Fig. 2.10 (b).

iii) Current Dependent Voltage Source : It produces a voltage as a function of current elsewhere in the given circuit. This is called **CDVS.** It is shown in the Fig. 2.10 (c).

iv) Voltage Dependent Current Source : It produces a current as a function of voltage elsewhere in the given circuit. This is called **VDCS.** It is shown in the Fig. 2.10 (d).

Fig. 2.10

K is constant and V_1 and I_1 are the voltage and current respectively, present elsewhere in the given circuit. The dependent sources are also known as controlled sources.

In this chapter, d.c. circuits consisting of independent d.c. voltage and current sources are analysed.

2.5.1 Limitations of Ohm's Law

The limitations of the Ohm's law are,

1) It is not applicable to the nonlinear devices such as diodes, zener diodes, voltage regulators etc.
2) It does not hold good for non-metallic conductors such as silicon carbide. The law for such conductors is given by,

$$V = k\, I^m \quad \text{where k, m are constants.}$$

2.6 Series Circuit

A series circuit is one in which several resistances are connected one after the other. Such connection is also called **end to end connection** or **cascade** connection. There is only one path for the flow of current.

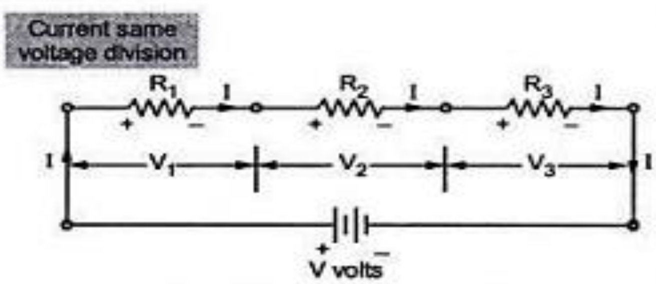


Fig. 2.12 A series circuit

Consider the resistances shown in the Fig. 2.12.

The resistance R_1, R_2 and R_3 are said to be in series. The combination is connected across a source of voltage V volts. Naturally the current flowing through all of them is same indicated as I amperes. e.g. the chain of small lights, used for the decoration purposes is good example of series combination.

Now let us study the **voltage distribution.**

Let V_1, V_2 and V_3 be the voltages across the terminals of resistances R_1, R_2 and R_3 respectively

Then, $$V = V_1 + V_2 + V_3$$

Now according to Ohm's law, $$V_1 = I R_1, \quad V_2 = I R_2, \quad V_3 = I\, R_3$$

Current through all of them is same i.e. I

$\therefore$ $$V = IR_1 + IR_2 + IR_3 = I(R_1 + R_2 + R_3)$$

Applying Ohm's law to overall circuit,

$$V = I\ R_{eq}$$

where R_{eq} = Equivalent resistance of the circuit. By comparison of two equations,

$$R_{eq} = R_1 + R_2 + R_3$$

i.e. total or **equivalent resistance** of the series circuit is arithmetic sum of the resistances connected in series.

For n resistences in series, $R = R_1 + R_2 + R_3 + \ldots\ldots + R_n$

2.6.1 Characteristics of Series Circuits

1) The same current flows through each resistance.
2) The supply voltage V is the sum of the individual voltage drops across the resistances.

$$V = V_1 + V_2 + \ldots\ldots + V_n$$

3) The equivalent resistance is equal to the sum of the individual resistances.
4) The equivalent resistance is the largest of all the individual resistances.

i.e $$R > R_1\ ,\ R > R_2,\ \ldots\ldots R > R_n$$

2.7 Parallel Circuit

The parallel circuit is one in which several resistances are connected across one another in such a way that one terminal of each is connected to form a junction point while the remaining ends are also joined to form another junction point. Consider a parallel circuit shown in the Fig. 2.13.

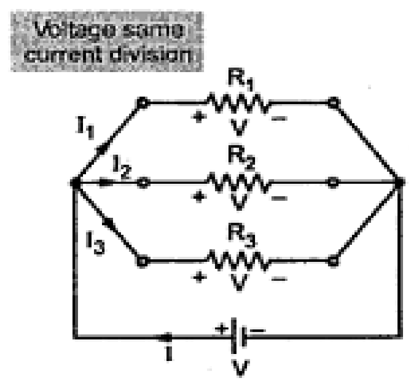


Fig. 2.13 A parallel circuit

In the parallel connection shown, the three resistances R_1, R_2 and R_3 are connected in parallel and combination is connected across a source of voltage 'V '.

In parallel circuit current passing through each resistance is different. Let total current drawn is say ' I ' as shown. There are 3 paths for this current, one through R_1, second through R_2 and third through R_3. Depending upon the values of R_1, R_2 and R_3 the appropriate fraction of total current passes through them. These individual currents are shown as I_1, I_2 and I_3. While the voltage across the two ends of each resistances R_1, R_2 and R_3 is the same and equals the supply voltage V.

Now let us study current distribution. Apply Ohm's law to each resistance.

$$V = I_1 R_1\ ,\ \ V = I_2 R_2\ ,\ \ V = I_3 R_3$$

$$I_1 = \frac{V}{R_1},\ I_2 = \frac{V}{R_2},\ I_3 = \frac{V}{R_3}$$

$$I = I_1 + I_2 + I_3 = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$= V\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right] \quad \dots (1)$$

For overall circuit if Ohm's law is applied,

$$V = I R_{eq}$$

and $$I = \frac{V}{R_{eq}} \quad \dots (2)$$

where R_{eq} = Total or equivalent resistance of the circuit

Comparing the two equations,

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

where R is the equivalent resistance of the parallel combination.

In general if 'n' resistances are connected in parallel,

$$\boxed{\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots + \frac{1}{R_n}}$$

Conductance (G) :

It is known that, $\frac{1}{R} = G$ (conductance) hence,

$$\therefore \quad \boxed{G = G_1 + G_2 + G_3 + \dots + G_n} \quad \dots \text{For parallel circuit}$$

Important result :

Now if n = 2, two resistances are in parallel then,

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\therefore \quad \boxed{R = \frac{R_1 R_2}{R_1 + R_2}}$$

This formula is directly used hereafter, for two resistances in parallel.

2.7.1 Characteristics of Parallel Circuits

1) The same potential difference gets across all the resistances in parallel.
2) The total current gets divided into the number of paths equal to the number of resistances in parallel. The total current is always sum of all the individual currents.

$$I = I_1 + I_2 + I_3 + \dots + I_n$$

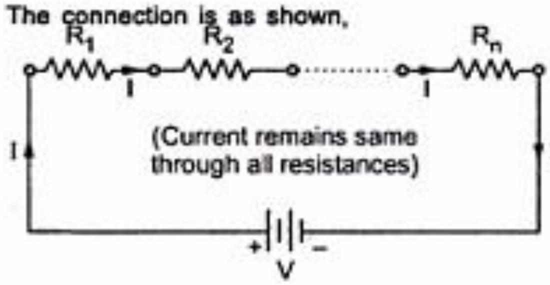
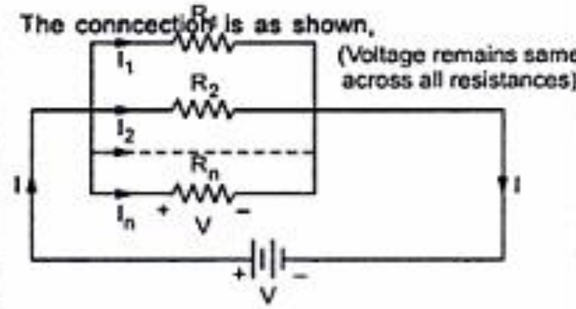
3) The reciprocal of the equivalent resistance of a parallel circuit is equal to the sum of the reciprocal of the individual resistances.
4) The equivalent resistance is the smallest of all the resistances.

$$R < R_1, \quad R < R_2, \dots, R < R_n$$

5) The equivalent conductance is the arithmetic addition of the individual conductances.

Key Point : *The equivalent resistance is smaller than the smallest of all the resistances connected in parallel.*

2.8 Comparison of Series and Parallel Circuits

Sr. No.	Series Circuit	Parallel Circuit
1.	The connection is as shown, 	The conncection is as shown, 
2.	The same current flows through each resistance.	The same voltage exists across all the resistances in parallel.
3.	The voltage across each resistance is different.	The current through each resistance is different.
4.	The sum of the voltages across all the resistances is the supply voltage. $V = V_1 + V_2 + V_3 + \ldots + V_n$	The sum of the currents through all the resistances is the supply current. $I = I_1 + I_2 + \ldots I_n$
5.	The equivalent resistance is, $R_{eq} = R_1 + R_2 + \ldots + R_n$	The equivalent resistance is, $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
6.	The equivalent resistance is the largest than each of the resistances in series. $R_{eq} > R_1, R_{eq} > R_2 \ldots R_{eq} > R_n$	The equivalent resistance is the smaller than the smallest of all the resistances in parallel.

Example 2.1 : *Find the equivalent resistance between the two points A and B shown in the Fig. 2.14.*

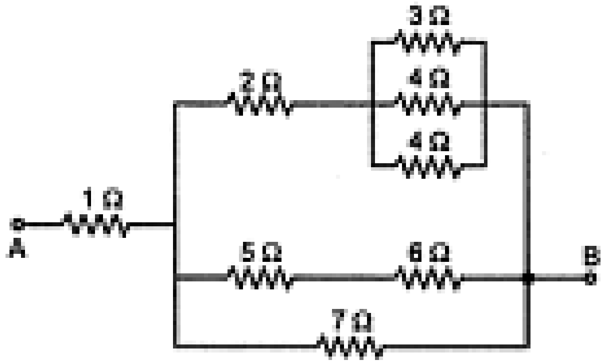


Fig. 2.14

Solution : Identify combinations of series and parallel resistances.

The resistances 5 Ω and 6 Ω are in series, as going to carry same current.

So equivalent resistance is 5 + 6 = 11 Ω

While the resistances 3 Ω , 4 Ω, and 4 Ω are in parallel, as voltage across them same but current divides.

∴ Equivalent resistance is, $$\frac{1}{R} = \frac{1}{3}+\frac{1}{4}+\frac{1}{4} = \frac{10}{12}$$

∴ $$R = \frac{12}{10} = 1.2\ \Omega$$

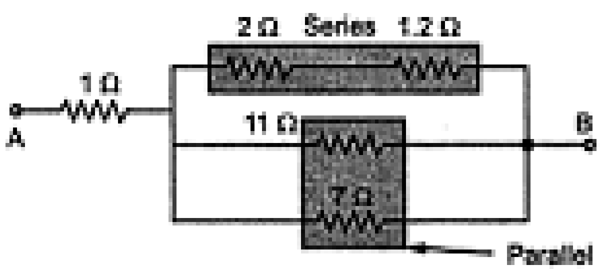


Fig. 2.14 (a)

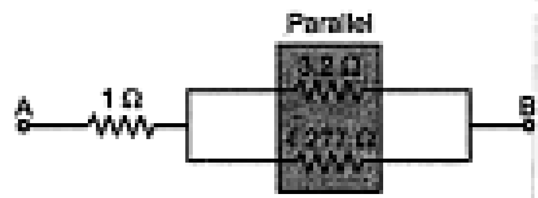


Fig. 2.14 (b)

Replacing these combinations redraw the figure as shown in the Fig. 2.14 (a).

Now again 1.2 Ω and 2 Ω are in series so equivalent resistance is 2 + 1.2 = 3.2 Ω while 11 Ω and 7 Ω are in parallel.

Using formula $\frac{R_1 R_2}{R_1 + R_2}$ equivalent resistance is $\frac{11\times 7}{11+7} = \frac{77}{18} = 4.277\Omega$.

Replacing the respective combinations redraw the circuit as shown in the Fig. 2.14 (b).

Now 3.2 and 4.277 are in parallel.

∴ Replacing them by $$\frac{3.2\times 4.277}{3.2+4.277} = 1.8304\ \Omega$$

∴ $$R_{AB} = 1+ 1.8304 = 2.8304\ \ \Omega$$

2.17 Superposition Theorem

This theorem is applicable for linear and bilateral networks. Let us see the statement of the theorem.

Statement : *In any multisource complex network consisting of linear bilateral elements, the voltage across or current through any given element of the network is equal to the algebraic sum of the individual voltages or currents, produced independently across or in that element by each source acting independently, when all the remaining sources are replaced by their respective internal resistances.*

The theorem is also known as Superposition principle. In other words, it can be stated as, the response in any element of linear, bilateral network containing more than one sources is the sum of the responses produced by the sources, each acting independently. The response means the voltage across the element or the current in the element. The superposition theorem does not apply to the power as power is proportional to square of the current, which is not a linear function.

2.17.1 Explanation of Superposition Theorem

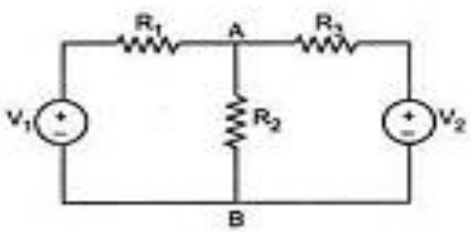


Fig. 2.63

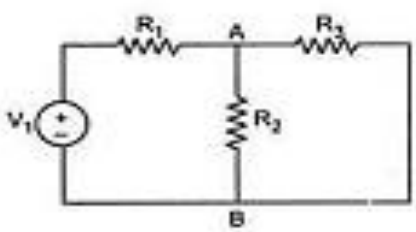


Fig. 2.63 (a)

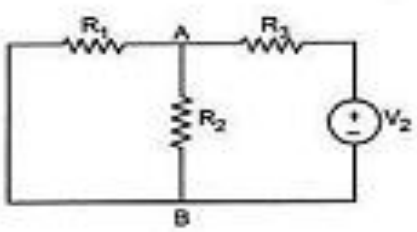


Fig. 2.63 (b)

Consider a network, shown in the Fig. 2.63, having two voltage sources V_1 and V_2.

Let us calculate, the current in branch A-B of the network, using superposition theorem.

Step 1) According to Superposition theorem, consider each source independently. Let source V_1 volts is acting independently. At this time, other sources must be replaced by internal impedances.

But as internal impedance of V_2 is not given, the source V_2 must be replaced by short circuit. Hence circuit becomes, as shown in the Fig. 2.63 (a).

Using any of the network reduction techniques discussed earlier, obtain the current through branch A-B i.e. I_{AB} due to source V_1 alone.

Step 2) Now consider source V_2 volts alone, with V_1 replaced by a short circuit, to obtain the current through branch A-B. The corresponding circuit is shown in the Fig. 2.63 (b).

Obtain I_{AB} due to V_2 alone, by using any of the network reduction techniques discussed earlier.

Step 3) According to the Superposition theorem, the total current through branch A-B is the sum of the currents through branch A-B produced by each source acting independently.

$$\therefore \quad \text{Total } I_{AB} = I_{AB} \text{ due to } V_1 + I_{AB} \text{ due to } V_2$$

2.17.2 Steps to Apply Superposition Theorem

Step 1 : Select a single source acting alone. Short the other voltage sources and open the current sources, if internal resistances are not known. If known, replace them by their internal resistances.

Step 2 : Find the current through or the voltage across the required element, due to the source under consideration, using a suitable network simplification technique.

Step 3 : Repeat the above two steps for all the sources

Step 4 : Add the individual effects produced by individual sources, to obtain the total current in or voltage across the element.

➡ **Example 2.22 :** *Use the Superposition theorem to calculate the current in branch PQ of the circuit shown in Fig. 2.64.* **(Dec. - 97)**

Solution : In a superposition principle, each source is to be considered independently.

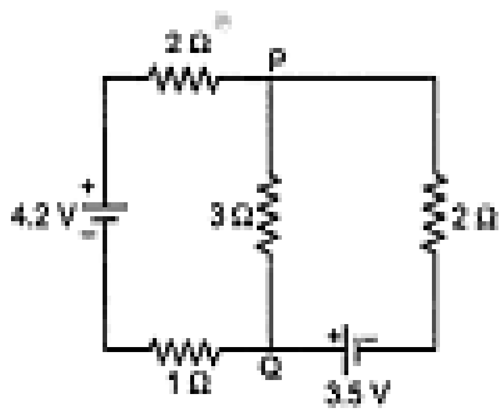


Fig. 2.64

Step 1 : Let us consider 4.2 V, replacing other by short circuit.

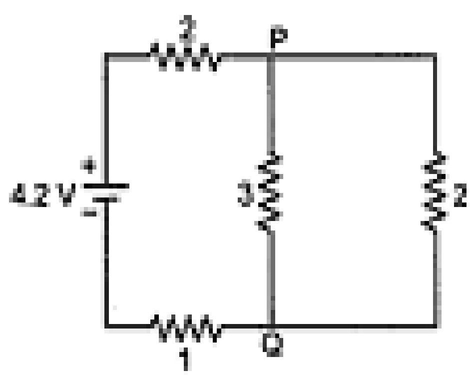


Fig. 2.64 (a)

The resistances 3 Ω and 2 Ω are in parallel

$$\therefore \quad 3 \parallel 2 = \frac{3\times 2}{3+2} = 1.2\ \Omega$$

$$\therefore \quad I = \frac{4.2}{(2+1.2+1)} = 1\ A$$

Now we want I_{PQ}, hence using current livision formula,

$$I'_{PQ} = 1\ A \times \frac{2}{2+3} = 0.4\ A \downarrow$$

... due to 4.2 V alone

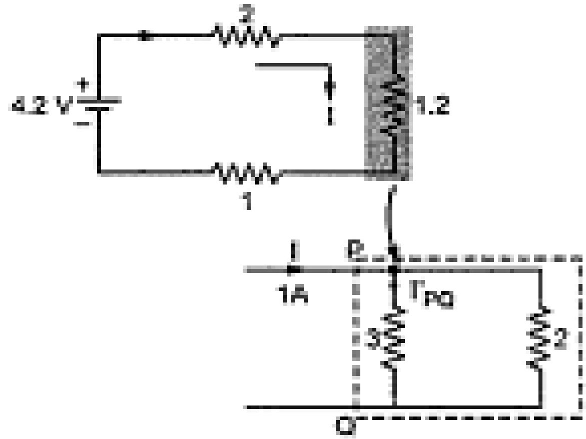


Fig. 2.64 (b)

Step 2 :

Now consider 3.5 V source, replacing other by a short circuit.

The resistances 2 and 1 are in series hence

2 series 1 = 2 + 1 = 3 Ω

The resistances 3 and 3 are in parallel.

$$\therefore \quad 3 \parallel 3 = \frac{3\times 3}{3+3} = 1.5\ \Omega$$

$$I = \frac{3.5}{(2+1.5)} = 1\ A$$

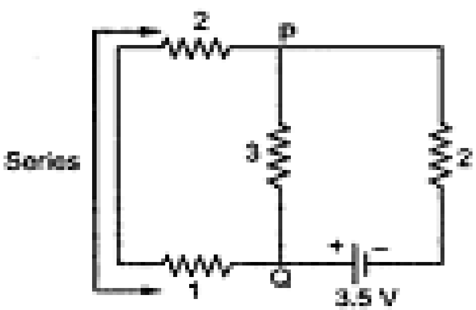


Fig. 2.64 (c)

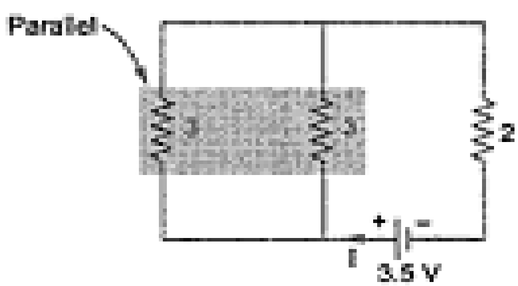


Fig. 2.64 (d)

But we want I_{PQ}, hence using current division formula we get,

$$I''_{PQ} = 1 \times \frac{3}{(3+3)}$$

$$= 1 \times \frac{3}{(3+3)}$$

$$= 0.5 \uparrow A$$

... due to 3.2 V alone

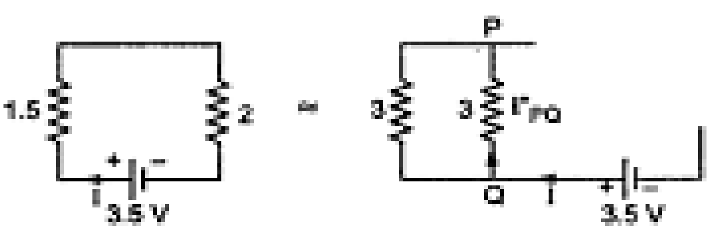


Fig. 2.64 (e)

Hence total current through PQ branch

$= 0.4\ A \downarrow + 0.5\ A \uparrow = 0.1\ A \uparrow$

Example 2.24 : *Use Superposition theorem to find the current through the 20 ohm resistance shown in the Fig. 2.66.* (May - 99)

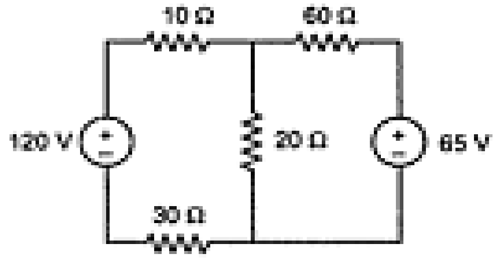


Fig. 2.66

Solution : Step 1 : Consider 120 V battery alone, shorting 65 V battery.

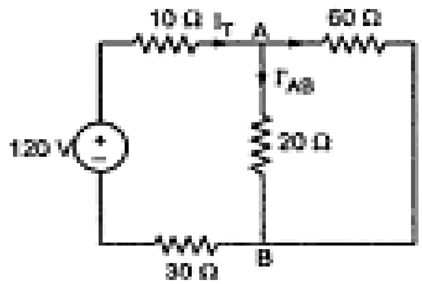


Fig. 2.66 (a)

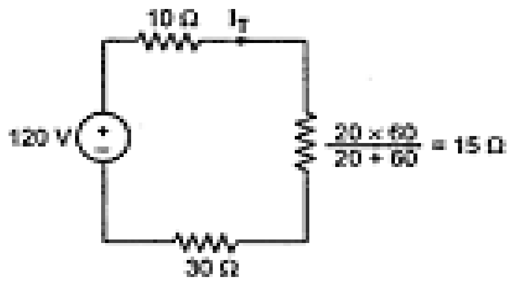


Fig. 2.66 (b)

$$\therefore \quad I_T = \frac{120}{10+15+30} = 2.1818 \text{ A}$$

$$\therefore \quad I'_{AB} = I_T \times \frac{60}{20+60} \qquad \text{... Current division rule}$$

$$= 1.6363 \text{ A due to 120 V battery} \downarrow$$

Step 2 : Consider 65 V battery alone, shorting 120 V battery.

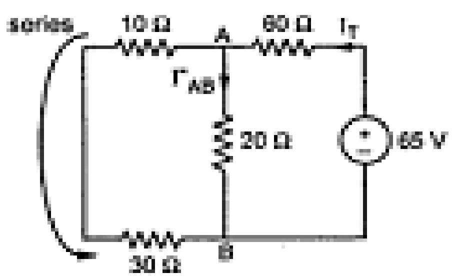


Fig. 2.66 (c)

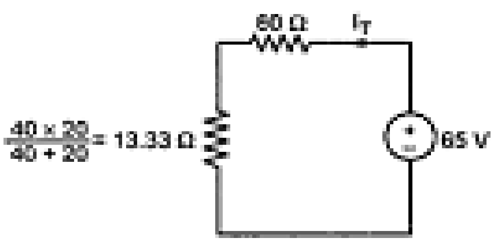


Fig. 2.66 (d)

$$I_T = \frac{65}{73.33} = 0.8863 \text{ A}$$

$$\therefore \quad I''_{AB} = I_T \times \frac{40}{20+40} = 0.5909 \text{ A due to 65 V battery} \downarrow$$

$\therefore$ Total current through 20 Ω resistance, according to Superposition theorem is,

$$I_{20\Omega} = 1.6363 + 0.5909 \text{ both in same direction}$$

$$= 2.2272 \text{ A} \downarrow$$

Example 2.25 : *In the circuit shown, find current through branch AB by Superposition theorem.* (Dec.-99)

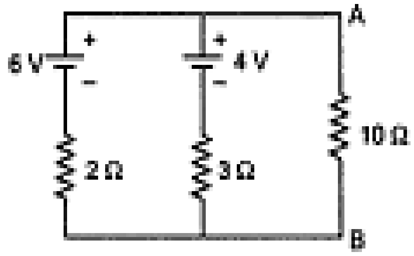


Fig. 2.67

Solution : Step 1 : Consider 6 V source alone

Now, resistances 10 Ω and 3 Ω are in parallel. Hence total current, I is

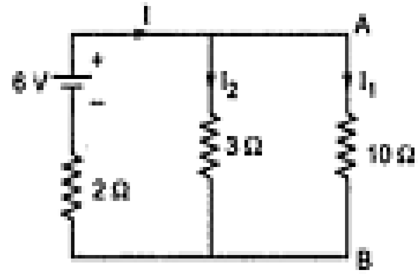


Fig. 2.67 (a)

$$I = \frac{6}{2+(3\|10)} = \frac{6}{2+\left(\frac{3\times10}{3+10}\right)} = \frac{6}{2+2.307}$$

$\therefore \quad I = 1.3928 \text{ A}$

As per current distribution in parallel branches,

$$I_1 = I\times\frac{3}{3+10} = \frac{1.3928\times3}{13} = 0.3214 \text{ A}\downarrow \quad \text{... (6 V alone)}$$

This is I_{AB} due to 6 V battery alone.

Step 2 : Consider 4 V battery alone.

Now, the resistances 2 Ω and 10 Ω are in parallel. Hence, current I can be obtained as,

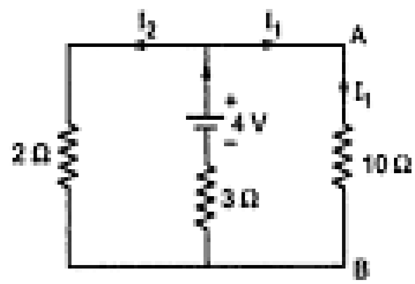


Fig. 2.67 (b)

$$I = \frac{4}{3+(2\|10)} = \frac{4}{3+\left(\frac{2\times10}{2+10}\right)}$$

$$= \frac{4}{3+1.67} = 0.8571 \text{ A}$$

According to current distribution in parallel branches,

$$I_1 = I\times\frac{2}{(2+10)} = 0.8571\times\frac{2}{12}$$

$$= 0.1428 \text{ A}\downarrow \quad \text{... (4 V alone)}$$

This is I_{AB} due to 4 V battery alone.

According to Superposition theorem,

$$\text{Total } I_{AB} = 0.3214 \text{ A}\downarrow + 0.1428 \text{ A}\downarrow = 0.4642 \text{ A}\downarrow \qquad \text{...Total current}$$

2.18 Thevenin's Theorem

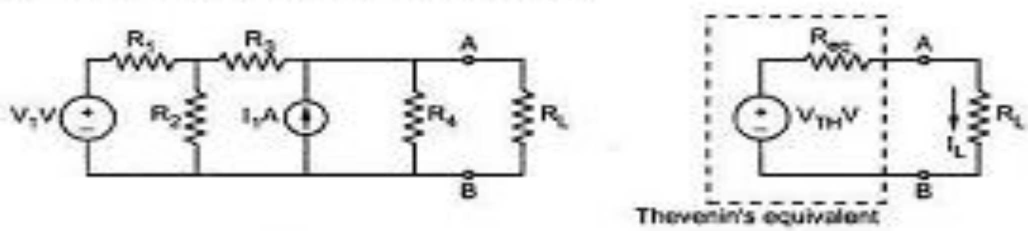
Let us see the statement of the theorem.

Statement : *Any combination of linear bilateral circuit elements and active sources, regardless of the connection or complexity, connected to a given load R_L, may be replaced by a simple two terminal network consisting of a single voltage source of V_{TH} volts and a single resistance R_{eq} in series with the voltage source, across the two terminals of the load R_L. The voltage V_{TH} is the open circuit voltage measured at the two terminals of interest, with load resistance R_L removed. This voltage is also called* ***Thevenin's equivalent voltage****. The R_{eq} is the* ***equivalent resistance*** *of the given network as viewed through the terminals where R_L is connected, but with R_L removed and all the active sources are replaced by their internal resistances.*

> **Key Point :** *If the internal resistances are not known then independent voltage sources are to be replaced by the short circuit while the independent current sources must be replaced by the open circuit.*

2.18.1 Explanation of Thevenin's Theorem

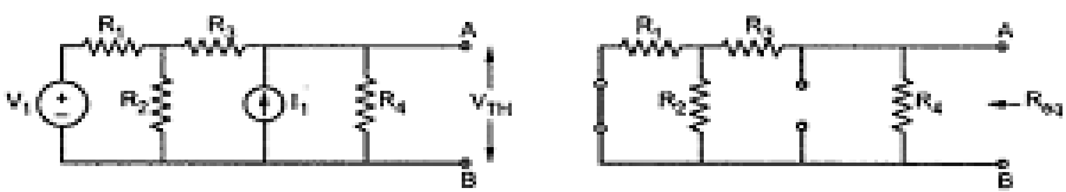
The concept of Thevenin's equivalent across the terminals of interest can be explained by considering the circuit shown in the Fig. 2.68 (a). The terminals A-B are the terminals of interest across which R_L is connected. Then Thevenin's equivalent across the load terminals A-B can be obtained as shown in the Fig. 2.68 (b).



(a) (b)

Fig. 2.68

The voltage V_{TH} is obtained across the terminals A-B with R_L removed. Hence V_{TH} is also called open circuit Thevenin's voltage. The circuit to be used to calculate V_{TH} is shown in the Fig. 2.69 (a), for the network considered above. While R_{eq} is the equivalent resistance obtained as viewed through the terminals A-B with R_L removed, voltage sources replaced by short circuit and current sources by open circuit. This is shown in the Fig. 2.69 (b).



(a) Calculation of V_{TH} **Fig. 2.69** **(b) Calculation of R_{eq}**

While obtaining V_{TH}, any of the network simplification techniques can be used.

When the circuit is replaced by Thevenin's equivalent across the load resistance, then the load current can be obtained as,

$$\boxed{I_L = \frac{V_{TH}}{R_L + R_{eq}}}$$

By using this theorem, current through any branch of the circuit can be obtained, treating that branch resistance as the load resistance and obtaining Thevenin's equivalent across the two terminals of that branch.

2.18.2 Steps to Apply Thevenin's Theorem

Step 1 : Remove the branch resistance through which current is to be calculated.

Step 2 : Calculate the voltage across these open circuited terminals, by using any of the network simplification techniques. This is V_{TH}.

Step 3 : Calculate R_{eq} as viewed through the two terminals of the branch from which current is to be calculated by removing that branch resistance and replacing all independent sources by their internal resitances. If the internal reistances are not known then replace independent voltage sources by short circuits and independent current sources by open circuits.

Step 4 : Draw the Thevenin's equivalent showing source V_{TH}, with the resistance R_{eq} in series with it, across the terminals of branch of interest.

Step 5 : Reconnect the branch resistance. Let it be R_L. The required current through the branch is given by,

$$I = \frac{V_{TH}}{R_{eq} + R_L}$$

2.18.3 Limitations of Thevenin's Theorem

The limitations of Thevenin's theorem are,

1. Not applicable to the circuits consisting of nonlinear elements.
2. Not applicable to unilateral networks.
3. There should not be magnetic coupling between the load and circuit to be replaced by Thevenin's theorem.
4. In the load side, there should not be controlled sources, controlled from some other part of the circuit.

➡ **Example 2.26 :** *For the circuit shown in the Fig. 2.70 find the Thevenin's equivalent across 16 Ω resistance and hence find the current through it.* **(May - 84)**

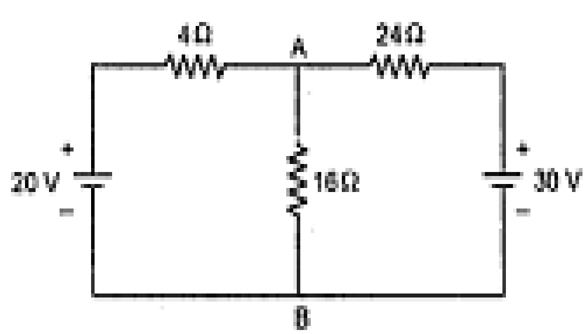


Fig. 2.70

Solution : Step 1 : Remove 16 Ω resistance.

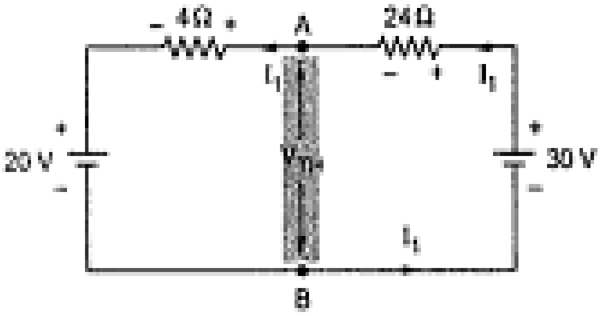


Fig. 2.70 (a)

Step 2 : Find open circuit voltage V_{TH}.

$\therefore -24\, I_1 - 4I_1 - 20 + 30 = 0$

$\therefore\ 28\, I_1 = 10$

$\therefore \quad I_1 = \frac{10}{28}$ A

$\therefore$ Drop across 4 Ω is $= \frac{10}{28} \times 4$

$= 1.4285$ V

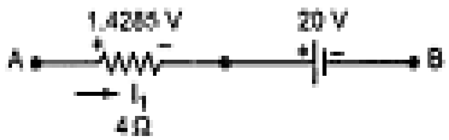


Fig. 2.70 (b)

Trace the path from A to B and arrange the voltage drops as shown in the Fig. 2.70 (b).

$\therefore\ V_{AB} = V_{TH} = 20 + 1.4285$

$= \mathbf{21.4285\ V}$ **with A positive**

Step 3 : Calculate R_{eq} shorting both the voltage sources.

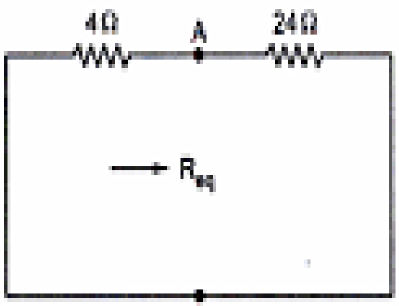


Fig. 2.70 (c)

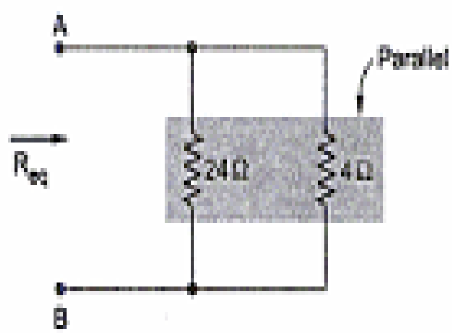


Fig. 2.70 (d)

$\therefore \qquad R_{eq} = R_{AB} = 24 \parallel 4 = 3.4285\ \Omega$

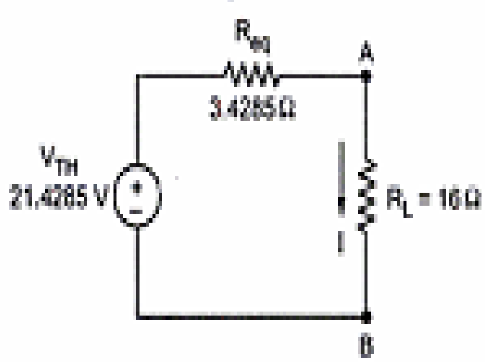


Fig. 2.70 (e)

Step 4 : Thevenin's equivalent is shown in the Fig. 2.70 (e).

Step 5 : Hence current I is,

$$I = \frac{V_{TH}}{R_{eq} + R_L} = \frac{21.4285}{3.4285 + 16}$$

$= 1.1029$ A ↓

2.19 Norton's Theorem

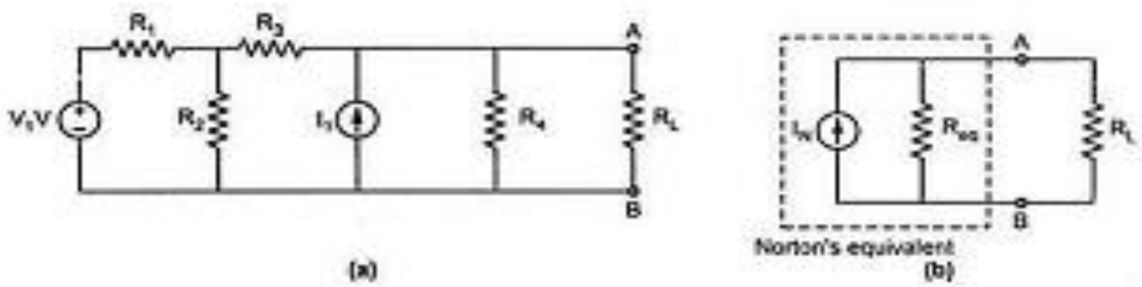
The Norton's theorem can be stated as below,

Statement : *Any combination of linear bilateral circuit elements and active sources, regardless of the connection or complexity, connected to a given load R_L, can be replaced by a simple two terminal network, consisting of a single current source of I_N amperes and a single impedance R_{eq} in parallel with it, across the two terminals of the load R_L. The I_N is the short circuit current flowing through the short circuited path, replaced instead of R_L. It is also called* ***Norton's current.*** *The R_{eq} is the equivalent impedance of the given network as viewed through the load terminals, with R_L removed and all the active sources are replaced by their internal impedances. If the internal impedances are unknown then the independent voltage sources must be replaced by short circuit while the independent current sources must be replaced by open circuit, while calculating R_{eq}.*

Key Point : *Infact the calculation of R_{eq} and its value remains same, whether the theorem applied to the network is Thevenin or Norton, as long as terminals of interest remain same.*

2.19.1 Explanation of Norton's Theorem

Consider the network shown in the Fig. 2.72 (a). The terminals A-B are the load terminals where R_L is connected. According to the Norton's theorem, the network can be replaced by a current source I_N with equivalent resistance R_{eq} parallel with it, across the load terminals, as shown in the Fig. 2.72 (b).



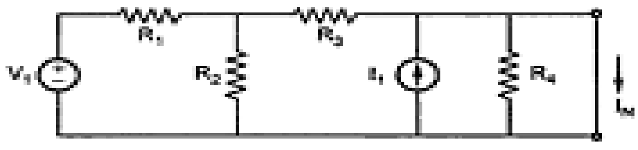


Fig. 2.73 (a)

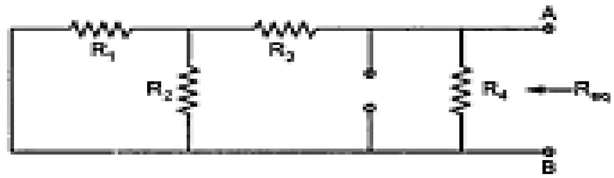


Fig. 2.73 (b)

For obtaining the current I_N, short the load terminals AB as shown in the Fig. 2.73 (a). Then find current I_N by using any of the network simplification techniques discussed earlier. This is Norton's current. While to calculate R_{eq} use same procedure as discussed earlier for Thevenin's theorem. For the convenience of reader circuit for calculation of R_{eq} is shown in the Fig. 2.73 (b).

This theorem is called dual of the Thevenin's theorem. This is because, if the Thevenin's equivalent voltage source is converted to equivalent current source using source transformation, we get the Norton's equivalent. This is shown in the Fig. 2.73 (c).

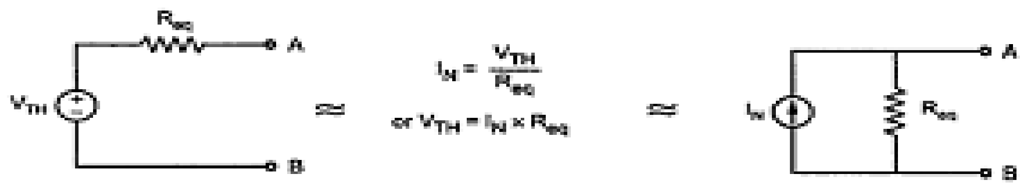


Fig. 2.73 (c)

2.19.2 Steps to Apply Norton's Theorem

Step 1 : Short the branch through which the current is to be calculated.

Step 2 : Obtain the current through this short circuited branch, using any of the network simplification techniques. This current is Norton's current I_N.

Step 3 : Calculate the equivalent resistance R_{eq}, as viewed through the terminals of interest, by removing the branch resistance and making all the independent sources inactive.

Step 4 : Draw the Norton's equivalent across the terminals of interest, showing a current source I_N with the resistance R_{eq} parallel with it.

Step 5 : Reconnect the branch resistance. Let it be R_L. Then using current division in parallel circuit of two resistances, current through the branch of interest can be obtained as,

$$I = I_N \times \frac{R_{eq}}{R_{eq} + R_L}$$

Example 2.28 : *Using Thevenin's theorem determine the current flowing through 2 Ω resistance in the network shown in Fig. 2.74.* (Dec.-2005)

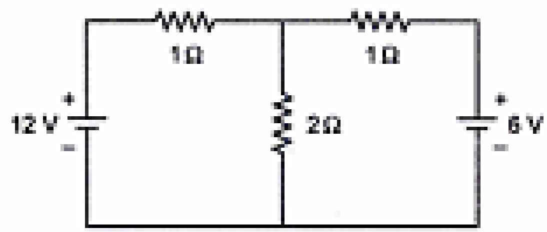


Fig. 2.74

Verify the answer using Norton's theorem.

Sol. : Thevenin's theorem :

Step 1 : Remove 2 Ω resistance.

Step 2 : Find open circuit voltage V_{TH}.

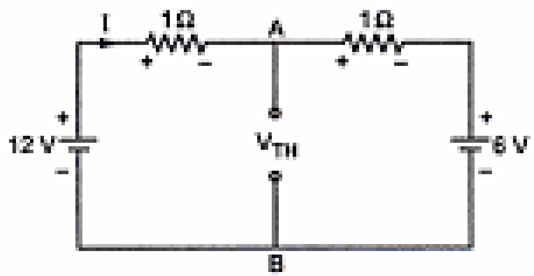


Fig. 2.74 (a)

Applying KVL to the loop,

$$-I - I - 6 + 12 = 0$$

$\therefore$ $2I = 6$ i.e. $I = 3$ A

Drop across $1\Omega = 3 \times 1 = 3$ V

Tracing path from A to B through 12 V source as shown in the Fig. 2.75 (b).

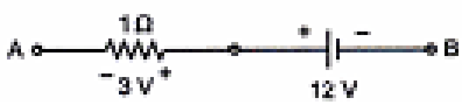


Fig. 2.74 (b)

$$\therefore \quad V_{AB} = V_{TH}$$

$$= 12 - 3 = 9 \text{ V} \quad \text{with A positive}$$

Step 3 : Calculate R_{eq}, shorting voltage sources.

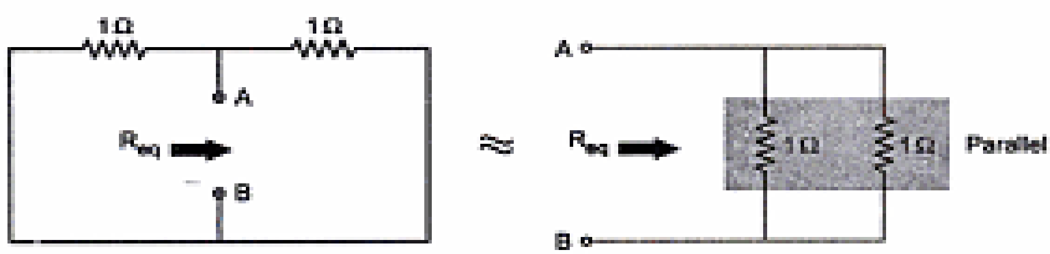


Fig. 2.74 (c)

$\therefore \quad R_{eq} = 1 \parallel 1 = 0.5\ \Omega$

Step 4 : Thevenin's equivalent is shown in the Fig. 2.74 (d).

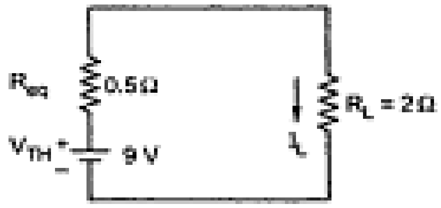


Fig. 2.74 (d)

Step 5 : Current through 2 Ω is,

$$I_L = \frac{V_{TH}}{R_L + R_{eq}} = 3.6\ \text{A} \downarrow$$

Norton's Theorem :

Step 1 : Short the branch of 2 Ω.

Step 2 : Calculate the short circuit current I_N.

Apply KVL to the two loops,

$$-I_1 + 12 = 0 \quad \text{i.e. } I_1 = 12\ \text{A} \qquad \text{... Loop I}$$

$$-(I_1 - I_N) - 6 = 0 \qquad \text{... Loop II}$$

$$\therefore \quad -I_1 + I_N - 6 = 0$$

$$\therefore \quad I_N = 6 + I_1 = 18\ \text{A}$$

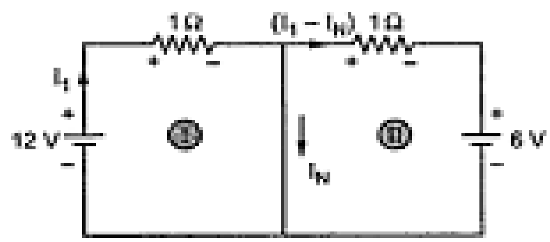


Fig. 2.75 (a)

Step 3 : Calculate R_{eq} shorting voltage sources. This is same as calculated above.

$$\therefore \quad R_{eq} = 0.5\ \Omega$$

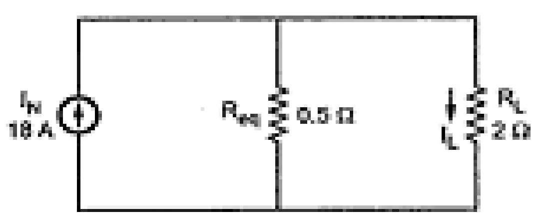


Fig. 2.75 (b)

Step 4 : Norton's equivalent is shown in the Fig. 2.75 (b).

Step 5 : Current through 2 Ω is,

$$I_L = I_N \times \frac{R_{eq}}{R_L + R_{eq}} = \frac{18 \times 0.5}{2.5} = 3.6\ \text{A} \downarrow$$

Substitute the value of K,

$$-\ln\left[\frac{V}{R} - i(t)\right] = \frac{R}{L}\cdot t - \ln\left[\frac{V}{R}\right]$$

$$\ln\left[\frac{V}{R} - i(t)\right] - \ln\left[\frac{V}{R}\right] = -\frac{R}{L}\cdot t$$

$$\ln\left[\frac{\frac{V}{R} - i(t)}{\frac{V}{R}}\right] = -\frac{R}{L}\cdot t$$

Applying Antilog,

$$\left[\frac{\frac{V}{R} - i(t)}{\frac{V}{R}}\right] = e^{-\frac{R}{L}\cdot t}$$

$$\Rightarrow \quad i(t) = \frac{V}{R} - \frac{V}{R}\cdot e^{-\frac{R}{L}t} \text{ A} \longrightarrow (5)$$

Above eq represents the solution of first order non-homogeneous differential Equation obtained by applying KVL to the driven series RL circuit.

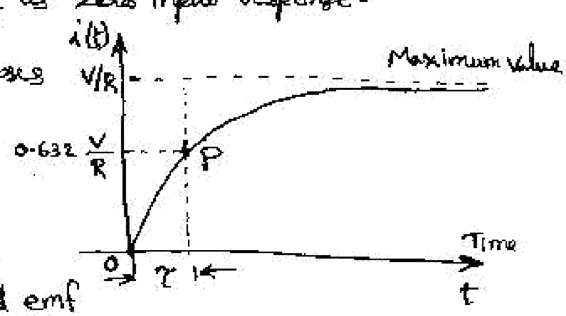
Above response is a combination of steady state response (forced response) and transient response (Natural response)

Forced response is denoted by $\frac{V}{R}$ and is due to forcing function ie, Applied voltage, V.

This is also called as the Zero state or steady state response.

Transient Response is denoted by term $\frac{V}{R}\cdot e^{-\frac{R}{L}t}$ in which 't' is involved.

This is a natural response and also called as Zero input response.



From figure, it is clear that, current increases exponentially wrt time.

This rising current produces rising flux, which induces emf in the coil

According to lenz's law, the self induced emf opposes the flow of current. Because of this property, current in the coil does not reach it maximum value instantaneously.

From the figure, current rises to P (0.632 times max value) in steady state.

The time required for the current to reach this value is called as time constant of given R-L circuit. It is denoted by τ.

$$\tau = \frac{L}{R} \text{ sec}$$

To determine the significance of τ, substitute $T = \tau, 2\tau, 4\tau, 6\tau \ldots$ in Eq (5)

At $t = \tau \quad i(t) = 0.632 \frac{V}{R}$

$t = 2\tau \quad i(t) = 0.8646 \frac{V}{R}$

$t = 4\tau \quad i(t) = 0.9816 \frac{V}{R}$

$t = 6\tau \quad i(t) = 0.9975 \frac{V}{R}$

It is clear from the above values that current rises to first τ in less time. but after one τ period, this rate slows down for further period of time. Ideally current reaches to steady state at infinite time, but practically it reaches steady state current value by $t = 6\tau$ (or) 8τ.

Voltage across inductor is

$$V_L(t) = L\frac{di(t)}{dt}$$

by substituting values of $i(t)$ from equation (5)

$$V_L(t) = L\frac{d}{dt}\left[\frac{V}{R}\left(1-e^{-\frac{R}{L}t}\right)\right]$$

$$V_L(t) = L\left[\underbrace{\frac{d}{dt}\left(\frac{V}{R}\right)}_{0} - \frac{d}{dt}\left(\frac{V}{R}\cdot e^{-\frac{R}{L}t}\right)\right]$$

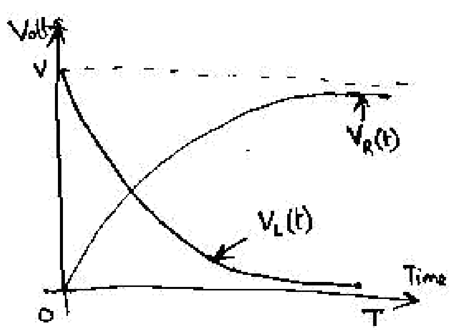
$$V_L(t) = \cancel{L}\left[-\left(\frac{V}{\cancel{R}}\right)\left(\frac{-\cancel{R}}{\cancel{L}}\right)\cdot e^{-\frac{R}{L}t}\right]$$

$$\therefore \boxed{V_L(t) = V\cdot e^{-R/L\cdot t}}$$

Voltage across Resistor is given by,

$$V_R(t) = R\cdot i(t) = R\left[\frac{V}{R} - \frac{V}{R}\cdot e^{-\frac{R}{L}t}\right]$$

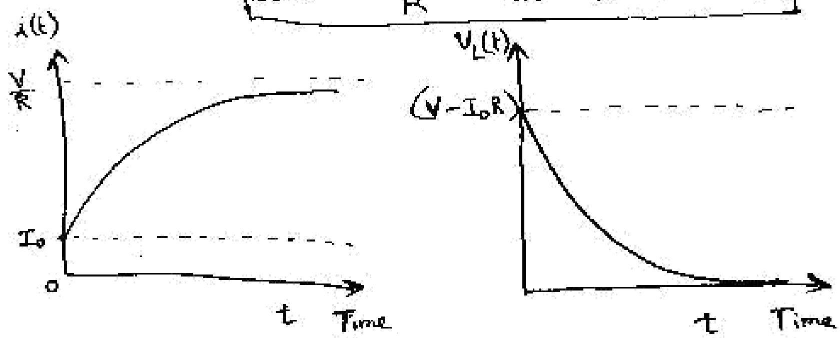
$$\Rightarrow V_R(t) = V - V\cdot e^{-\frac{R}{L}t} = V\left(1-e^{-\frac{R}{L}t}\right) \text{ Volts}$$



Current through inductor increases exponentially
Voltage across resistor also increases Exponentially but
Voltage across inductor decreases exponentially.
When the current reaches its steady state value at infinite time, the voltage across inductor also reaches its steady state value ie, zero.
Thus in steady state as voltage across inductor is zero, it acts as a short circuit.

Considering the Series RL circuit, let us assume that inductor carries initial current I_0 before switching action. Then expression of current flowing through inductor is given by

$$\boxed{i(t) = \frac{V}{R} - \left(\frac{V}{R} - I_0\right) \cdot e^{-\frac{R}{L}t} \quad A}$$



Transient Response of $i(t)$ & $V_L(t)$ with inductor carrying some initial current.

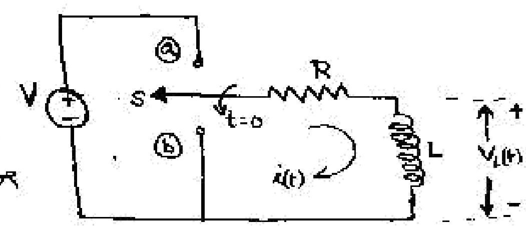
Expression for voltage generated across inductor,

$$\boxed{V_L(t) = (V - I_0 \cdot R) \cdot e^{-\frac{R}{L}t} \quad V}$$

The above response is called Zero-State Response. It is a response to a non-zero input to a circuit with zero initial conditions. Also it is a "Driven circuit."

Transient Response of Source Free (or) Undriven Series R-L Circuit:-

Consider a Series R-L Circuit,

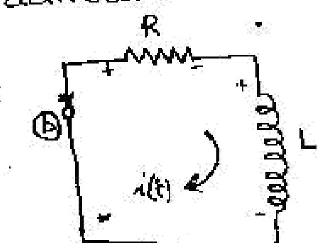


At ⓐ with switch closed initially for very long time before transition. It indicates that the network before transition is in steady state. So inductor acts as short circuit.

$\therefore$ At $t = 0^-$ $\quad i(0^-) = I_0 = \frac{V}{R} = i(0^+)$

For all $t \geq 0^+$ switch is moved to ⓑ position,

Now the network is without any excitation (or) active source. Hence such a circuit is called Source free (or) undriven circuit. As the initial steady state condition is disturbed now, inductor is not shortcircuited in this case.



Applying KVL, $\quad -R \cdot i(t) - L\frac{di(t)}{dt} = 0$

$$i(t) = \frac{-L}{R}\frac{di(t)}{dt}$$

Seperating Variables, $\quad \frac{di(t)}{i(t)} = \frac{-R}{L}dt$

Integrating both the sides wrt corresponding variables,

$$\ln(i(t)) = \frac{-R}{L}.t + K \qquad \text{where } K - \text{arbitary constant}$$

Find K using initial condition values,

At $t=0$; $i(t) = I_0$

$$\Rightarrow \ln(I_0) = \frac{-R}{L} \times 0 + K \Rightarrow K = \ln[I_0]$$

by substituting K value,

$$\ln(i(t)) = -\frac{R}{L}t + \ln[I_0]$$

$$\Rightarrow \ln[i(t)] - \ln[I_0] = -\frac{R}{L}.t$$

$$\ln\left[\frac{i(t)}{I_0}\right] = -\frac{R}{L}t$$

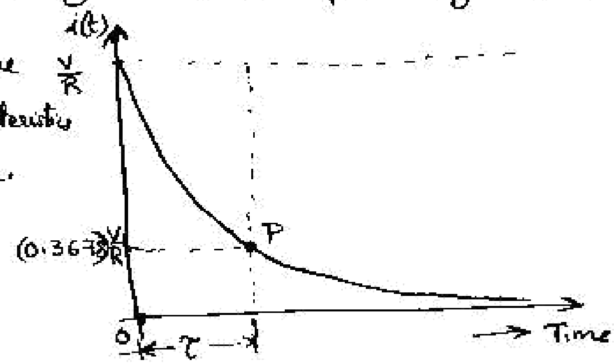
by Antilog,

$$\frac{i(t)}{I_0} = e^{-\frac{R}{L}.t}$$

$$\Rightarrow i(t) = I_0 \cdot e^{-\frac{R}{L}.t} \Rightarrow \boxed{i(t) = \frac{V}{R} \cdot e^{\frac{R}{L}t} \text{ A}}$$

So it is evident that current through inductor exponentially decreases.

At Point P on the graph, the current value $\frac{V}{R}$ is (0.368) times its maximum value. The characteristic of decay is determined by the values of R & L.



$\because \quad \tau = \frac{L}{R}$

for $t = \tau$, $i(t) = I_0 \cdot e^{-1} = (0.3678)I_0$

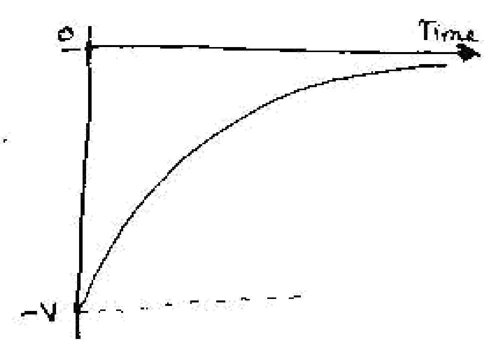
$t = 2\tau$, $i(t) = I_0 \cdot e^{-2} = (0.1353)I_0$

$t = 4\tau$, $i(t) = I_0 \cdot e^{-4} = (0.0183)I_0$

$t = 6\tau$, $i(t) = I_0 \cdot e^{-6} = (0.0024)I_0$

$t = \infty$, $i(t) = I_0 \cdot e^{-\infty} = 0$

For the above values, it is clears that current decreases rapidly to 0.3678 times initial maximum value over first τ, Then rate of decay slows down and reaches steadystate at $t = 6\tau$ or 8τ.

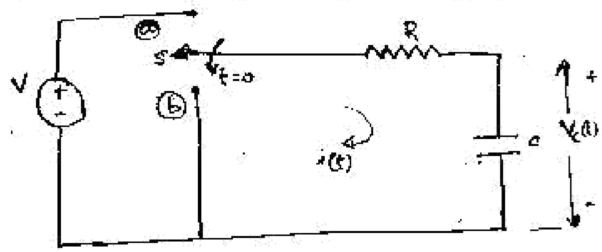


$$V_L(t) = L\frac{di}{dt} = L\frac{d}{dt}\left[I_0 \cdot e^{-\frac{R}{L}t}\right] = \cancel{L} \cdot I_0 \cdot \frac{-R}{\cancel{L}} \cdot e^{-\frac{R}{L}t}$$

$$\Rightarrow \boxed{V_L(t) = -I_0 \cdot R \cdot e^{-\frac{R}{L}t}} \quad ; \text{ But } I_0 \cdot R = V$$

$$\Rightarrow \boxed{V_L(t) = -V \cdot e^{-\frac{R}{L}t} \text{ Volts}}$$

Transient Response of Source Free (or) Undriven Series RC Circuit:-



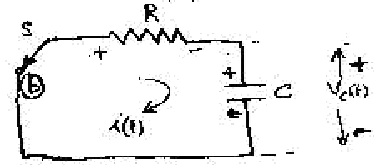
Initially at $t=0^-$ Switch is in (a) Position

At $t=0$; Switch is moved to (b) position

Here we will find the discharge of Capacitor through resistor expressed as Voltage across capacitor as a function of time(t)

$\therefore$ At $t=0^-$ Switch is in position (a) Network in steady state & $C \rightarrow$ O.C

$\therefore\ V_c(0^-) = V_0 = V = V_c(0^+) \longrightarrow (1)$



For All $t \geq 0$ Switch is moved to position (b)

Now Network is without excitation and called as Sourcefree (or) undriven series RC circuit. Now voltage across capacitor varies exponentially, steady state is disturbed.

By applying KVL,

$$i(t) \cdot R + V_c(t) = 0 \longrightarrow (2)$$

$$RC \cdot \frac{dV_c(t)}{dt} = -V_c(t) \qquad \because i(t) = C\frac{dV_c(t)}{dt}$$

seperating variables,

$$\frac{dV_c(t)}{V_c(t)} = \frac{-1}{RC}dt$$

Integrating on both sides with respect to corresponding variables

$$\ln[V_c(t)] = \frac{-t}{RC} + K \longrightarrow (3)$$

find K; At $t=0$; $V_c(t) = V_0 = V$

$$\ln[V_0] = \frac{-0}{RC} + K \Rightarrow K = \ln[V_0] \longrightarrow (4)$$

Substituting K in (3),

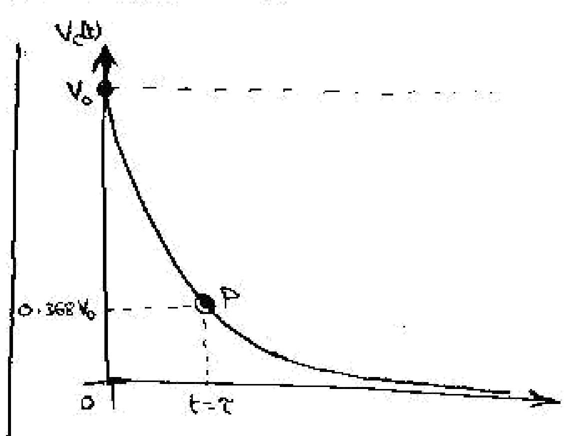
$$\ln[V_c(t)] = \frac{-t}{RC} + \ln[V_0]$$

$$\ln[V_c(t)] - \ln[V_0] = \frac{-t}{RC}$$

$$\ln\left[\frac{V_c(t)}{V_0}\right] = \frac{-t}{RC}$$

Take Antilog,

$$\boxed{V_c(t) = V_0 \cdot e^{-\frac{t}{RC}} \text{ Volts}}$$



For $t=\tau$; $V_c(t) = 0.368\,V_0$ | $t=4\tau$; $V_c(t) = 0.0183\,V_0$

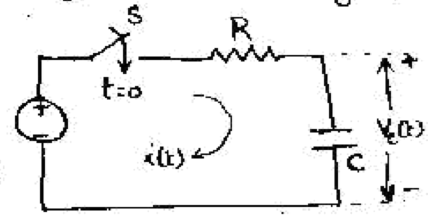
$=2\tau$; $V_c(t) = 0.1353\,V_0$ | 6τ; $V_c(t) = 0.0024\,V_0$

Transient Response of Series RC Circuit for DC Excitation :-

In the Series R C Circuit, capacitor may be initially charged (or) uncharged. As we analyse driven Series RC circuit and undriven (or) Source free Series RC circuit, we obtain the solution for each case.

Transient Response of Driven Series RC circuit :-

Consider a Series RC Circuit which is having switch initially open for very long time at $t=0$ it is closed.



At $t=0^-$ Switch is open.

$$\therefore V_c(0^-) = V_0 = 0 = V_c(0^+) \longrightarrow (1)$$

For all $t \geq 0$ Switch S is closed,

Apply KVL,

$$Ri(t) + V_c(t) - V = 0$$

$$Ri(t) + V_c(t) = V \longrightarrow (2)$$

$$\because i(t) = C\frac{dV_c(t)}{dt}$$

$$RC\frac{dV_c(t)}{dt} + V_c(t) = V$$

$$RC\frac{dV_c(t)}{dt} = V - V_c(t)$$

Seperating Variables,

$$\frac{dV_c(t)}{(V-V_c(t))} = \frac{1}{RC}dt \longrightarrow (3)$$

Integrating both sides wrt corresponding Variables,

$$-\ln(V - V_c(t)) = \frac{t}{RC} + K \longrightarrow (4)$$

To find K, initial conditions, At $t=0$; $V_c(t)=0$

$$-\ln(V-0) = \frac{0}{RC} + K \Rightarrow K = -\ln(V) \longrightarrow (5)$$

Substituting K,

$$-\ln(V - V_c(t)) = \frac{t}{RC} - \ln(V)$$

$$\ln(V - V_c(t)) - \ln(V) = \frac{-t}{RC}$$

$$\ln\left(\frac{V - V_c(t)}{V}\right) = \frac{-t}{RC}$$

Antilog :-

$$V - V_c(t) = V \cdot e^{-\frac{1}{RC}t} \Rightarrow \boxed{V_c(t) = V - V \cdot e^{-\frac{1}{RC}t}\ V} \longrightarrow (6)$$

Eq ⑥ is the Solution of first order differential equation for driven Series RC ckt.
Value of t can be between t = 0 to t = ∞ (Positive Values) to obtain $V_c(t)$.
The expression is a combination of steady state response (V) & transient response ($V.e^{-\frac{t}{RC}}$)

$$i(t) = i_c(t) = C \cdot \frac{d(V_c(t))}{dt}$$

$$= C \cdot \frac{d}{dt}\left[V - V.e^{-\frac{t}{RC}}\right]$$

$$i(t) = \cancel{C}\left[0 - V \cdot \frac{-1}{R\cancel{C}} \cdot e^{-\frac{t}{RC}}\right]$$

$$\boxed{i(t) = \frac{V}{R} \cdot e^{-\frac{t}{RC}}\ A} \longrightarrow ⑦$$

$\tau = RC$ sec

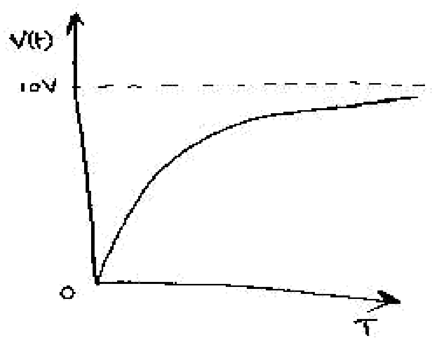
For $t = \tau$; $V_c(t) = V - V \cdot e^{-1} = 0.632V$

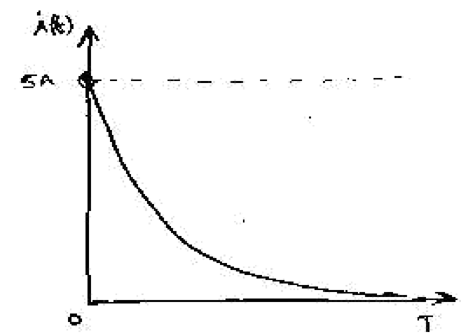
$t = 2\tau$; $V_c(t) = V - V \cdot e^{-2} = 0.8646V$

$t = 4\tau$; $V_c(t) = V - V \cdot e^{-4} = 0.9816V$

$t = 6\tau$; $V_c(t) = V - V \cdot e^{-6} = 0.9975V$

From the above values, it is clear that at $t = \tau$, voltage across capacitor rapidly rises to 0.632 times steady state value, then rate of increase slowsdown.





UNIT-II

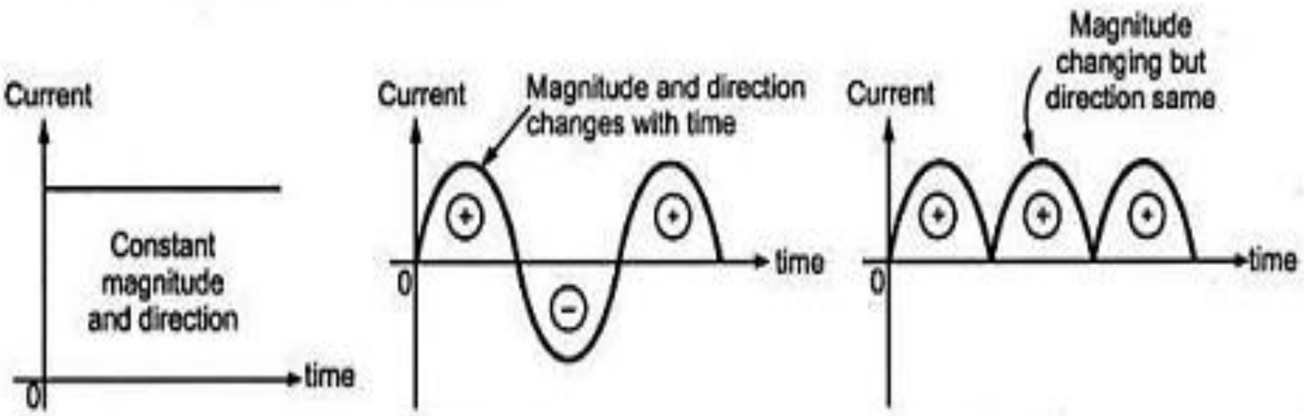
Alternating Quantities

6.1 Introduction

Uptill now, we have discussed about D.C. supply and D.C. circuits. But 90 % of electrical energy used now a days is a.c. in nature. Electrical supply used for commercial purposes is alternating. The d.c. supply has constant magnitude with respect to time. The Fig. 6.1(a) shows a graph of such current with respect to time.

> **Key Point**: *An alternating current (a.c.) is the current which changes periodically both in magnitude and direction.*

Such change in magnitude and direction is measured in terms of cycles. Each cycle of a.c. consists of two half cycles namely positive cycle and negative cycle. Current increases in magnitude, in one particular direction, attains maximum and starts decreasing, passing through zero it increases in opposite direction and behaves similarly. The Fig. 6.1 (b) shows a graph of alternating current against time.



(a) Direct current (b) Alternating current (c) Pulsating d.c.

Fig. 6.1

In practice some waveforms are available in which magnitude changes but its direction remains same as positive or negative. This is shown in the Fig. 6.1(c). Such waveform is called **pulsating d.c.** The waveform obtained as output of full wave rectifier is an example of pulsating d.c.

Let us see, why in practice, there is generation of a.c. Use of a.c. definitely offers certain advantages.

6.2 Advantages of A.C.

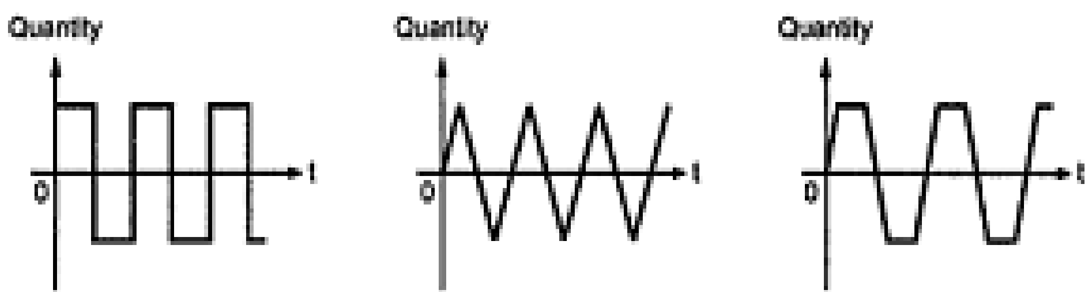
The various advantages of a.c. are,

1. The voltages in a.c. system can be raised or lowered with the help of a device called transformer. In d.c. system, raising and lowering of voltages is not so easy.
2. As the voltages can be raised, electrical transmission at high voltages is possible. Now, higher the voltage, lesser is the current flowing through transmission line. Less the current, lesser are the copper losses and lesser is the conducting material required. This makes a.c. transmission always economical and efficient.
3. It is possible to build up high a.c. voltage; high speed a.c. generators of large capacities. The construction and cost of such generators are very low. High a.c. voltages of about 11 kV can be generated and can be raised upto 220 kV for transmission purpose at sending end, while can be lowered down at 400 V at receiving end. This is not possible in case of d.c.
4. A.C. electrical motors are simple in construction, are cheaper and require less attention from maintenance point of view.
5. Whenever it is necessary, a.c. supply can be easily converted to obtain d.c. supply. This is required as d.c. is very much essential for the applications like cranes, printing process, battery charging, telephone system, etc. But, such requirement of d.c. is very small compared to a.c.

Due to these advantages, a.c. is used extensively in practice and hence, it is necessary to study a.c. fundamentals.

6.3 Types of A.C. Waveforms

The waveform of alternating voltage or current is shown purely sinusoidal in the Fig. 6.1 (b). But, in practice, a quantity which undergoes variations in its instantaneous values, in magnitude as well as direction with respect to some zero reference is called an alternating quantity. The graph of such quantity against time is called its waveform. Various types of alternating waveforms other than sinusoidal are shown in the Fig. 6.2 (a), (b) and (c).



(a) Square (b) Triangular (c) Trapezoidal

Fig. 6.2

Out of all these types of alternating waveforms, purely sinusoidal waveform is preferred for a.c. system. There are few advantages of selecting purely sinusoidal as the standard waveform.

6.3.1 Advantages of Purely Sinusoidal Waveform

1) Mathematically, it is very easy to write the equations for purely sinusoidal waveform.

2) Any other type of waveform can be resolved into a series of sine or cosine waves of fundamental and higher frequencies, sum of all these waves gives the original wave form. Hence, it is always better to have sinusoidal waveform as the standard waveform.

3) The sine and cosine waves are the only waves which can pass through linear circuits containing resistance, inductance and capacitance without distortion. In case of other waveforms, there is a possibility of distortion when it passes through a linear circuit.

4) The integration and derivative of a sinusoidal function is again a sinusoidal function. This makes the analysis of linear electrical networks with sinusoidal inputs, very easy.

6.4 Generation of A.C. Voltage

The machines which are used to generate electrical voltages are called **generators.** The generators which generate purely sinusoidal a.c. voltages are called **alternators.**

The basic principle of an alternator is the principle of electromagnetic induction. The sine wave is generated according to **Faraday's law of electromagnetic induction.** It says that whenever there is a relative motion between the conductor and the magnetic field in which it is kept, an e.m.f. gets induced in the conductor. The relative motion may exist because of movement of conductors with respect to magnetic field or movement of magnetic field with respect to conductor. Such an induced e.m.f. then can be used to supply the electrical load.

6.7 Effective Value or R.M.S. Value

An alternating current varies from instant to instant, while the direct current is constant, with respect to time. So, for the comparison of the two, there must be some common platform. Such platform can be the effect produced by the two currents. One of the such effects is heating of the resistance, due to current passing through it. The heating effect can be used to compare the alternating and direct current. From this, r.m.s. value of an alternating current can be defined as,

> **Key Point:** *The effective or r.m.s. value of an alternating current is given by that steady current (D.C.) which, when flowing through a given circuit for a given time, produces the same amount of heat as produced by the alternating current, which when flowing through the same circuit for the same time.*

The following simple experiment gives the clear understanding of the r.m.s. value of an alternating current. The arrangement is shown in the Fig. 6.11.

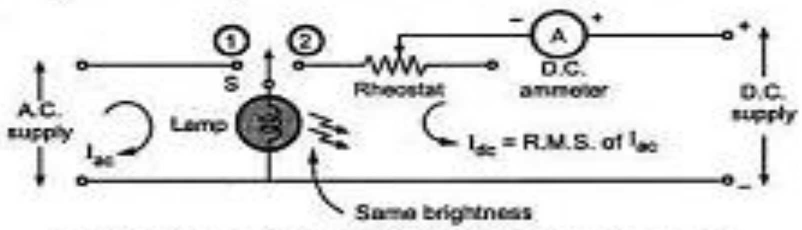


Fig. 6.11 Experiment to demonstrate r.m.s. value

A lamp is provided with double throw switch S. On position 1, it gets connected to an a.c. supply. The brightness of filament is observed.

Then, switch is thrown in position 2 and using the rheostats, the d.c. current is adjusted so as to achieve the same brightness of the filament.

The reading on the ammeter on d.c. side gives the value of the direct current that produces the same heating effect as that produced by the alternating current. This ammeter reading is nothing but the r.m.s. value of the alternating current.

R.M.S. value can be determined by two methods :

1) **Graphical Method** : This can be used for an alternating current having any wave form i.e. sinusoidal, triangular, square, etc.

2) **Analytical Method** : This is to be used for purely sinusoidally varying alternating current.

6.7.1 Graphical Method

Consider sinusoidally varying current.The r.m.s. value is to be obtained by comparing heat produced. Heat produced is proportional to square of current (i^2 R) so heat produced in both positive and negative half cycles will be the same. Hence, consider only positive half cycle, which is divided into 'n' intervals as shown in the Fig. 6.12. The width of each interval is 't/n' seconds and average height of each interval is assumed to be the average instantaneous values of current i.e. $i_1, i_2, ..., i_n$.

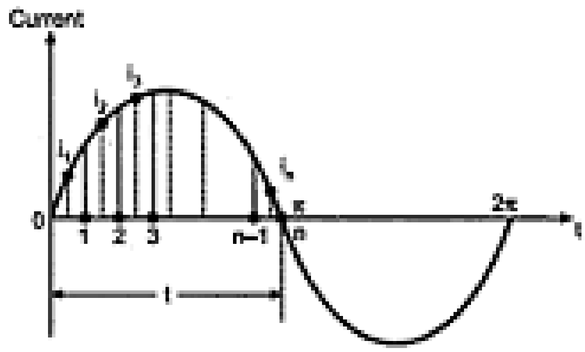


Fig. 6.12 Determining r.m.s. value

Let this current be passing through resistance 'R' ohms. Hence, heat produced can be calculated as,

joules $\quad$ Heat Produced $= i^2 R t$ $\quad$ joules

$\therefore$ Heat produced due to 1st interval $= i_1^2 R \frac{t}{n}$ $\quad$ joules

$\therefore$ Heat produced due to 2nd interval $= i_2^2 R \frac{t}{n}$ $\quad$ joules

$\therefore$ Heat produced due to nth interval $= i_n^2 R \frac{t}{n}$ $\quad$ joules

$\therefore$ Total heat produced in 't' seconds $= R \times t \times \frac{[i_1^2 + i_2^2 + ... + i_n^2]}{n}$

Now, heat produced by direct current I amperes passing through same resistance 'R' for the same time 't' is $= I^2 R t$ joules

For I to be the r.m.s. value of an alternating current, these two heats must be equal.

$$\therefore \quad I^2 R t = R \times t \times \frac{[i_1^2 + i_2^2 + ... + i_n^2]}{n}$$

$$\therefore \quad I^2 = \frac{[i_1^2 + i_2^2 + ... + i_n^2]}{n}$$

$$\therefore \quad \boxed{I = \sqrt{\frac{[i_1^2 + i_2^2 + ... + i_n^2]}{n}} = I_{r.m.s.}}$$

$I_{r.m.s.}$ = square root of the mean of the squares of ordinates of the current.

This is called **Effective value** of an alternating current or **Virtual value** of an alternating current. This expression is equally applicable to sinusoidally varying alternating voltage as,

$$V_{r.m.s.} = \sqrt{\frac{[V_1^2 + V_2^2 + ... + V_n^2]}{n}}$$

6.7.2 Analytical Method

Consider sinusoidally varying alternating current and square of this current as sh
n the Fig. 6.13.

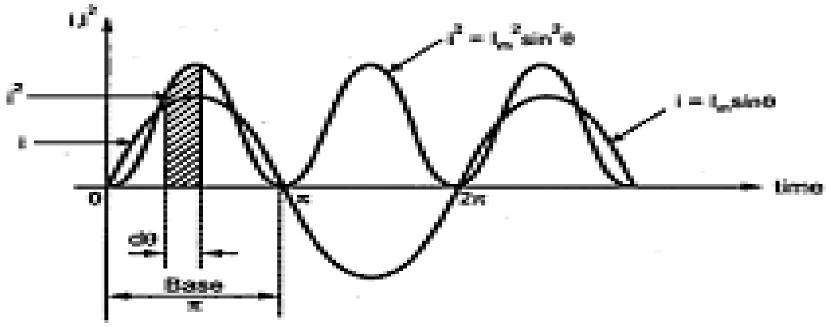


Fig. 6.13 Waveform of current and square of the current

The current $i = I_m \sin\theta$ while

square of current $i^2 = I_m^2 \sin^2\theta$

Area of curve over half a cycle can be calculated by considering an interval dθ
shown.

Area of square curve over half cycle $= \int_0^{\pi} i^2\, d\theta$ and Length of the base is π.

$\therefore$ Average value of square of the current over half cycle

$$= \frac{\text{Area of curve over half cycle}}{\text{Length of base over half cycle}} = \frac{\int_0^{\pi} i^2\, d\theta}{\pi}$$

$$= \frac{1}{\pi}\int_0^{\pi} i^2\, d\theta = \frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2\theta\, d\theta = \frac{I_m^2}{\pi}\left[\frac{1-\cos 2\theta}{2}\right] d\theta$$

$$= \frac{I_m^2}{\pi}\left[\theta - \frac{\sin 2\theta}{2}\right]_0^{\pi} = \frac{I_m^2}{2\pi}[\pi]$$

$$= \frac{I_m^2}{2}$$

Hence, root mean square value i.e. r.m.s. value can be calculated as,

$$I_{r.m.s.} = \sqrt{\text{mean or average of square of current}} = \sqrt{\frac{I_m^2}{2}}$$

$$= \frac{I_m}{\sqrt{2}}$$

$$\therefore \qquad \boxed{I_{r.m.s.} = 0.707\ I_m}$$

The r.m.s. value of the sinusoidal alternating current is 0.707 times the maximum or peak value or amplitude of that alternating current.

Key Point : *The instantaneous values are denoted by small letters like i, e etc. while r.m.s. values are represented by capital letters like I, E etc.*

The above result is also applicable to sinusoidal alternating voltages.

So, we can write,

$$\therefore \qquad \boxed{V_{r.m.s.} = 0.707\ V_m}$$

6.7.3 Importance of R.M.S. Value

1. In case of alternating quantities, the r.m.s. values are used for specifying magnitudes of alternating quantities. The given values such as 230 V, 110 V are r.m.s. values of alternating quatntities unless and otherwise specicied to beother than r.m.s.

Key Point : *In practice, everywhere, r.m.s. values are used to analyze alternating quantities.*

2. The ammeters and voltmeters record the r.m.s. values of current and voltage respectively.
3. The heat produced due to a.c. is proportional to square of the r.m.s. value of the current.

Steps to find r.m.s. value of an a.c. quantity :

1. Write the equation of an a.c. quantity. Observe its behaviour during various time intervals.
2. Find square of the a.c. quantity from its equation.
3. Find average value of square of an alternating quantity as,

$$\text{Average} = \frac{\text{Area of curve over one cycle of squared waveform}}{\text{Length of the cycle}}$$

4. Find square root of average value which gives r.m.s. value of an alternating quantity.

$$\text{Time period } T = \frac{1}{f} = \frac{1}{50} = 0.02 \text{ sec}$$

$$\text{Time at A} = \frac{T}{4} = 0.005 \text{ sec}$$

i) $t_1 = 0.005 + 0.0025 = 0.0075$ sec

$\therefore$ $i = 14.1421 \sin(314.159 \times 0.0075) = 10$ **A**

ii) $\text{Time at C} = \dfrac{T}{2} = \dfrac{0.02}{2} = 0.01$ sec

$\therefore$ $t_2 = 0.01 + 0.0075 = 0.0175$ sec

$\therefore$ $i = 14.1421 \sin(314.159 \times 0.0175) = -10$ **A**

* Calculate sin in radian mode.

6.12 Phasor Representation of an Alternating Quantity

In the analysis of a.c. circuits, it is very difficult to deal with alternating quantities in terms of their waveforms and mathematical equations. The job of adding, subtracting, etc. of the two alternating quantities is tedious and time consuming in terms of their mathematical equations. Hence, it is necessary to study a method which gives an easier way of representing an alternating quantity. Such a representation is called phasor representation of an alternating quantity.

The sinusoidally varying alternating quantity can be represented graphically by a straight line with an arrow in this method. The length of the line represents the magnitude of the quantity and arrow indicates its direction. This is similar to a vector representation. Such a line is called a phasor.

Key Point: *The phasors are assumed to be rotated in anticlockwise direction.*

One complete cycle of a sine wave is represented by one complete rotation of a phasor. The anticlockwise direction of rotation is purely a conventional direction which has been universally adopted.

Consider a phasor, rotating in anticlockwise direction, with uniform angular velocity, with its starting position 'a' as shown in the Fig. 6.18. If the projections of this phasor on Y-axis are plotted against the angle turned through 'θ', (or time as $\theta = \omega t$), we get a sine waveform.

Consider the various positions shown in the Fig. 6.18.

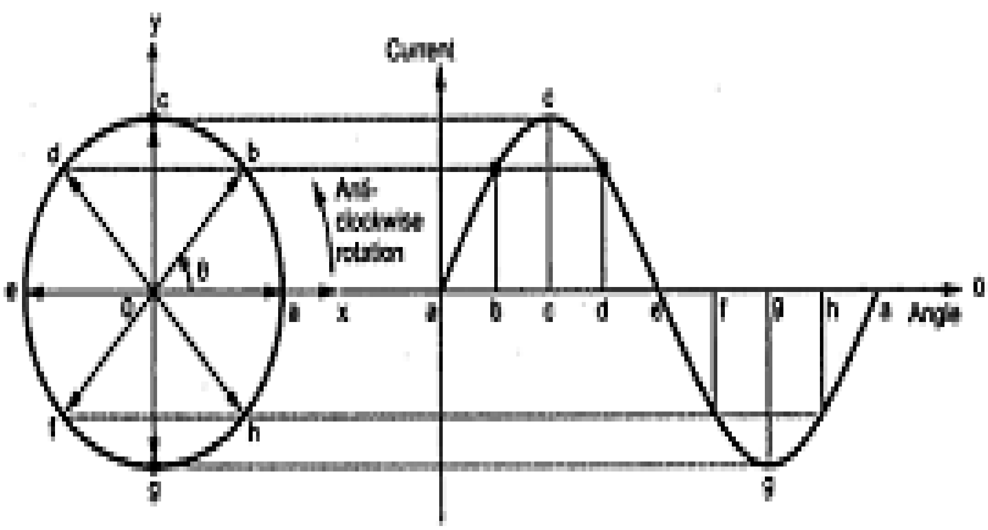


Fig. 6.18 Phasor representation of an alternating quantity

Phase : The phase of an alternating quantity at any instant is the angle ϕ (in radians or degrees) travelled by the phasor representing that alternating quantity upto the instant of consideration, measured from the reference.

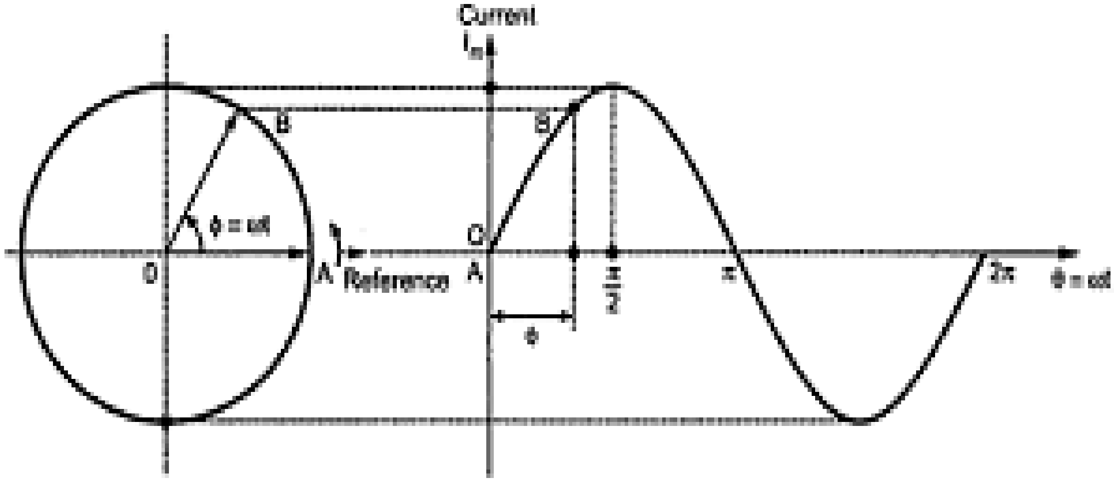


Fig. 6.19 Concept of phase

Let X-axis be the reference axis. So, phase of the alternating current shown in the Fig. 6.20 at the instant A is $\phi = 0°$. While the phase of the current at the instant B is the angle ϕ through which the phasor has travelled, measured from the reference axis i.e. X-axis.

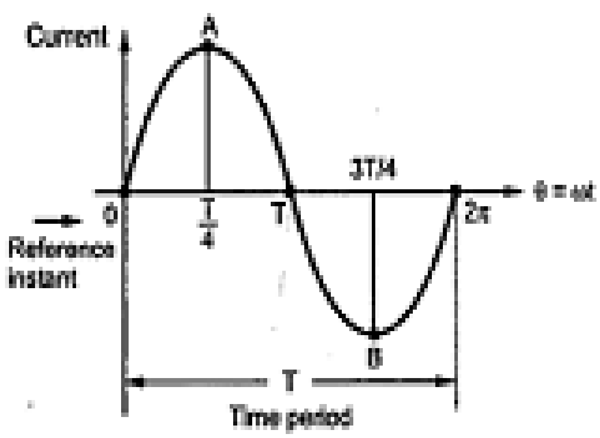


Fig. 6.20

In general, the phase ϕ of an alternating quantity varies from $\phi = 0$ to 2π radians or $\phi = 0°$ to $360°$.

Another way of defining the phase is in terms of a time period T. The phase of an alternating quantity at any particular instant is the fraction of the time period (T) through which the quantity is advanced from the reference instant.

Consider alternating quantity represented in the Fig. 6.20. As per above definition, the phase of quantity at instant A is $\frac{T}{4}$, while phase at instant B is $\frac{3T}{4}$. Generally, the phase is expressed in terms of angle ϕ which varies from 0 to 2π radians and measured with respect to positive x-axis direction.

In terms of phase the equation of alternating quantity can be modified as,

$$\boxed{e = E_m \sin(\omega t \pm \phi)}$$

where ϕ = Phase of the alternating quantity.

Let us consider three cases;

Case 1 : $\phi = 0°$

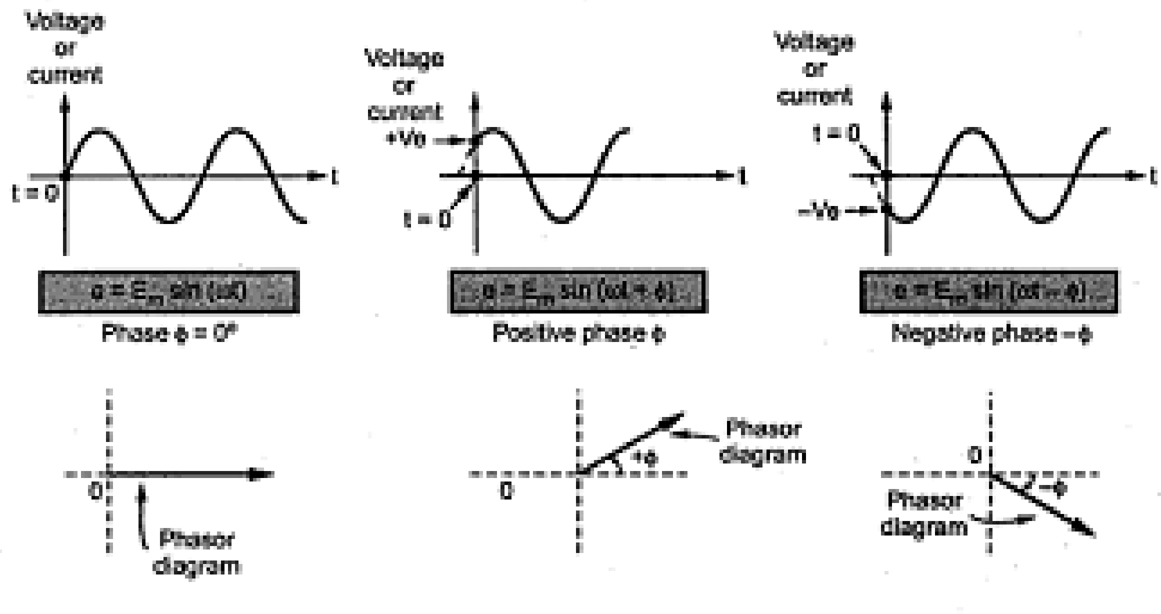
When phase of an alternating quantity is zero, it is standard pure sinusoidal quantity having instantaneous value zero at t = 0. This is shown in the Fig. 6.21 (a).

Case 2 : Positive phase ϕ

When phase of an alternating quantity is positive it means that quantity has some positive instantaneous value at t = 0. This is shown in the Fig. 6.21 (b).

Case 3 : Negative phase ϕ

When phase of an alternating quanting is negative it means that quantity has some negative instantaneous value at t = 0. This is shown in the Fig. 6.21 (c).



(a) Zero phase (b) Positive phase (c) Negative phase

Fig. 6.21 Concept of phase

1. The phase is measured with respect to reference direction i.e. positive x axis direction.
2. The phase measured in anticlockwise direction is positive while the phase measured in clockwise direction is negative.

6.13.1 Phase Difference

Consider the two alternating quantities having same frequency f Hz having different maximum values.

$$e = E_m \sin(\omega t)$$

and $$i = I_m \sin(\omega t)$$

where $$E_m > I_m$$

$$e = E_m \sin \omega t \quad \text{and} \quad i = I_m \sin(\omega t + \phi)$$

'i' is said to lead 'e' by angle ϕ

Key Point : *Thus, related to the phase difference, it can be remembered that a plus (+) sign of angle indicates lead where as a minus (–) sign of angle indicates lag with respect to the reference.*

6.13.2 Phasor Diagram

The diagram in which different alternating quantities of the same frequency, sinusoidal in nature are represented by individual phasors indicating exact phase interrelationships is known as **phasor diagram.**

The phasors are rotating in anticlockwise direction with an angular velocity of $\omega = 2\pi f$ rad/sec. Hence, all phasors have a particular fixed position with respect to each other.

Key Point : *Hence, phasor diagram can be considered as a still picture of these phasors at a particular instant.*

To clear this point, consider two alternating quantities in phase with each other.

$$e = E_m \sin \omega t \quad \text{and} \quad i = I_m \sin \omega t$$

At any instant, phase difference between them is zero i.e. angle difference between the two phasors is zero. Hence, the phasor diagram for such case drawn at different instants will be alike giving us the same information that two quantities are in phase. The phasor diagram drawn at different instants are shown in the Fig. 6.25.

Fig. 6.25 Same phasor diagram at different instants

Consider another example where current i is lagging voltage e by angle ϕ. So, difference between the angles of the phasors representing the two quantities is angle ϕ.

$$e = E_m \sin \omega t$$

and $$i = I_m \sin(\omega t - \phi)$$

The phasor diagram for such case, at various instants will be same, as shown in the Fig. 6.26 (a), (b) and (c).

The phasor diagram drawn at any instant gives the same information.

Key Point : *Remember that the lagging and leading word is relative to the reference. In the above case, if we take current as reference, we have to say that the voltage leads current by angle ϕ. The direction of rotation of phasors is always anticlockwise.*

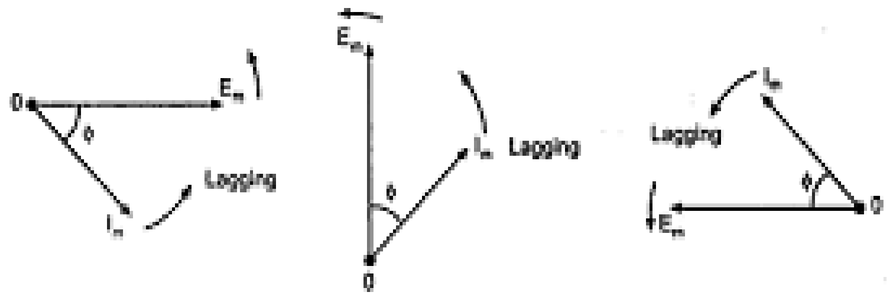


Fig. 6.26

Important Points Regarding Phasor Diagram :

1) As phasor diagram can be drawn at any instant, X and Y axis are not included in it. But, generally, the reference phasor chosen is shown along the positive X axis direction and at that instant other phasors are shown. This is just from convenience point of view. **The individual phase of an alternating quantity is always referred with respect to the positive x-axis direction.**

2) There may be more than two quantities represented in phasor diagram. Some of them may be current and some may be voltages or any other alternating quantities like flux, etc. The frequency of all of them must be the same.

3) Generally, length of phasor is drawn equal to r.m.s. value of an alternating quantity, rather than maximum value.

4) The phasors which are ahead, in anticlockwise direction, with respect to reference phasor are said to be leading with respect to reference and phasors behind are said to be lagging.

5) Different arrow heads may be used to differentiate phasors drawn for different alternating quantities like current, voltage, flux, etc.

Example 6.8 : *Two sinusoidal currents are given by,*

$i_1 = 10 \sin(\omega t + \pi/3)$ *and*

$i_2 = 15 \sin(\omega t - \pi/4)$

Calculate the phase difference between them in degrees.

Solution : The phase of current i_1 is $\pi/3$ radians i.e. $60°$ while the phase of the current i_2 is $-\pi/4$ radians i.e. $-45°$. This is shown in the Fig. 6.27.

Hence the phase difference between the two is,

$$\phi = \theta_1 - \theta_2 = 60° - (-45°) = 105°$$

And i_2 lags i_1.

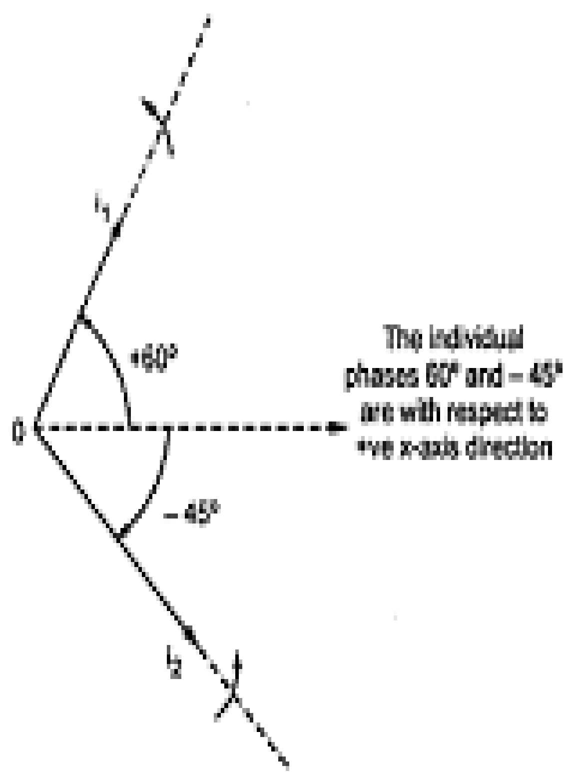


Fig. 6.27

Polar system,	$r \angle \pm \phi$ while	Rectangular system, $x \pm j\, y$	
and	$x = r\cos\phi$	$y = r\sin\phi$	...(1)
while	$r = \sqrt{x^2+y^2}$,	$\phi = \tan^{-1}\left(\frac{y}{x}\right)$	...(2)

The equations (1) and (2) can be used to convert rectangular form to polar or vice versa.

Such rectangular to polar and polar to rectangular conversion is often required in phasor mathematical operations like addition, subtraction, multiplication and division.

Key Point : *Instead of using above relations, students can use the polar to rectangular ($P \rightarrow R$) and rectangular to polar ($R \rightarrow P$) functions available on calculator for the required conversions.*

As the graphical method is time consuming which includes plotting the phasors to the scale, generally, analytical method is used. Also, graphical method may give certain error which will vary from person to person depending upon the skills of plotting the phasors. The answer by analytical method is always accurate.

Very Important :

The polar form of an alternating quantity can be easily obtained from its equation or phase as,

If $\quad e = E_m \sin(\omega t \pm \phi)$ then

E in polar $= E \angle \pm \phi$ *where E = r.m.s. value*

Example 6.9 : *Write the polar form of the voltage given by,*
$V = 100 \sin(100\,\pi\, t + \pi/6)\ V$

Obtain its rectangular form.

Solution : $V_m = 100\ V$ and $\phi = +\frac{\pi}{6}\ rad = +30°$, $\quad V_{rms} = \frac{V_m}{\sqrt{2}} = 70.7106\ V$

$\therefore$ In polar form $= 70.7106 \angle +30°\ V$

$\therefore$ Rectangular form $= 61.2371 + j\ 35.3553\ V$

Key Point: *The r.m.s. value of an alternating quantity exists in its polar form and not in rectangular form. Thus to find r.m.s. value of an alternating quantity express it in polar form.*

Example 6.10 : *Find r.m.s. value and phase of the current $I = 25 + j\,40\ A$.*

Solution : The r.m.s. value is not 25 or 40 as it exists in polar form.

Single Phase AC series Circuits:

7.1 Introduction

The resistance, inductance and capacitance are three basic elements of any electrical network. In order to analyze any electric circuit, it is necessary to understand the following three cases,

1) A.C. through pure resistive circuit.
2) A.C. through pure inductive circuit.
3) A.C. through pure capacitive circuit.

In each case, it is assumed that a purely sinusoidal alternating voltage given by the equation $v = V_m \sin(\omega t)$ is applied to the circuit. The equation for the current, power and phase shift are developed in each case. The voltage applied having zero phase angle is assumed reference while plotting the phasor diagram in each case.

Once the behaviour of pure R, L and C is discussed, then the various series and parallel combinations of R, L and C are discussed in this chapter. The concept of impedance, admittance, susceptance, phasor diagrams of series and parallel circuits and resonance in series and parallel circuits are also included in this chapter.

7.2 A.C. through Pure Resistance

Consider a simple circuit consisting of a pure resistance 'R' ohms connected across a voltage $v = V_m \sin \omega t$. The circuit is shown in the Fig. 7.1.

According to Ohm's law, we can find the equation for the current i as,

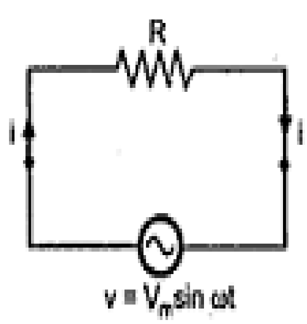


Fig. 7.1 Pure resistive circuit

$$i = \frac{v}{R} = \frac{V_m \sin \omega t}{R} \quad \text{i.e.} \quad i = \left(\frac{V_m}{R}\right) \sin(\omega t)$$

This is the equation giving instantaneous value of the current.

Comparing this with standard equation,

$$i = I_m \sin(\omega t + \phi)$$

$$\boxed{I_m = \frac{V_m}{R} \quad \text{and} \quad \phi = 0}$$

So, maximum value of alternating current, i is $I_m = \frac{V_m}{R}$ while, as $\phi = 0$, it indicates that it is in phase with the voltage applied. There is no phase difference between the two. The current is going to achieve its maximum (positive and negative) and zero whenever voltage is going to achieve its maximum (positive and negative) and zero values.

Key Point : *In purely resistive circuit, the current and the voltage applied are in phase with each other.*

The waveforms of voltage and current and the corresponding phasor diagram is shown in the Fig. 7.2 (a) and (b).

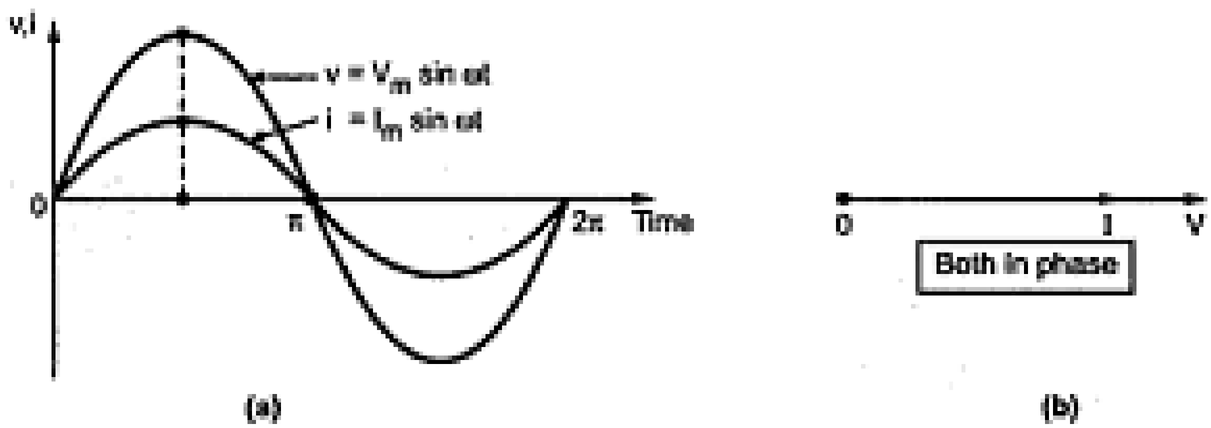


Fig. 7.2 A.C. through purely resistive circuit

In the phasor diagram, the phasors are drawn in phase and there is no phase difference in between them. Phasors represent the r.m.s. values of alternating quantities.

7.2.1 Power

The instantaneous power in a.c. circuits can be obtained by taking product of the instantaneous values of current and voltage.

$$P = v \times i = V_m \sin(\omega t) \times I_m \sin \omega t = V_m I_m \sin^2(\omega t)$$

$$= \frac{V_m I_m}{2}(1 - \cos 2\omega t)$$

$$\therefore \quad \boxed{P = \frac{V_m I_m}{2} - \frac{V_m I_m}{2}\cos(2\omega t)}$$

From the above equation, it is clear that the instantaneous power consists of two components.

1) Constant power component $\left(\frac{V_m I_m}{2}\right)$

2) Fluctuating component $\left[\frac{V_m I_m}{2} \cos(2\omega t)\right]$ having frequency, double the frequency of the applied voltage.

Now, the average value of the fluctuating cosine component of double frequency is zero, over one complete cycle. So, average power consumption over one cycle is equal to the constant power component i.e. $\frac{V_m I_m}{2}$.

$$\therefore \qquad P_{av} = \frac{V_m I_m}{2} = \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}}$$

$$\therefore \qquad \boxed{P_{av} = V_{rms} \times I_{rms} \quad \text{watts}}$$

Generally, r.m.s. values are indicated by capital letters

$$\therefore \qquad \boxed{P_{av} = V \times I \quad \text{watts} = I^2 R \quad \text{watts}}$$

The Fig. 7.3 shows the waveforms of voltage, current and power.

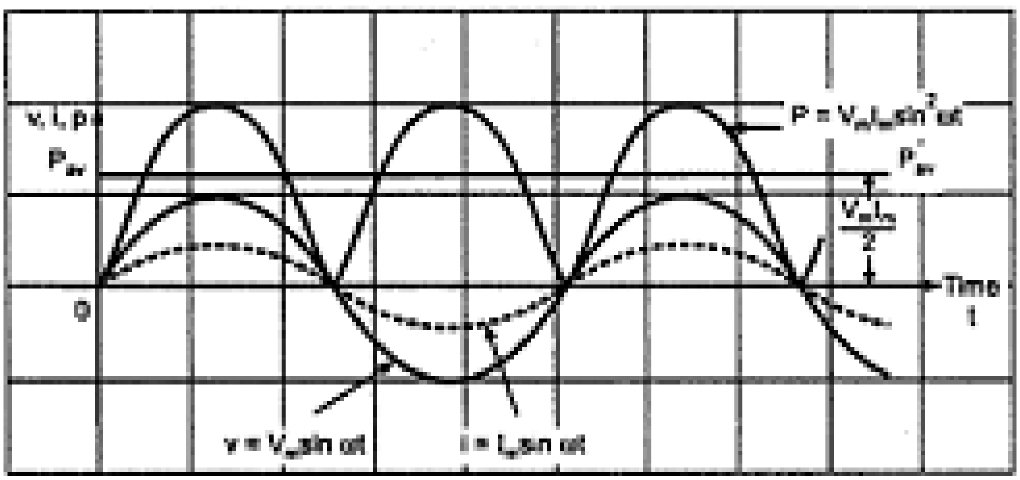


Fig. 7.3 v, i and p for purely resistive circuit

7.3 A.C. through Pure Inductance

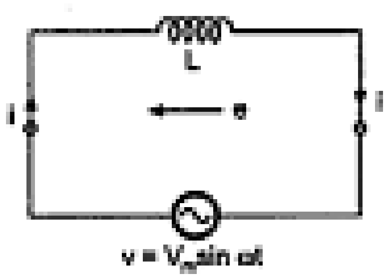


Fig. 7.4 Purely inductive circuit

Consider a simple circuit consisting of a pure inductance of L henries, connected across a voltage given by the equation, $v = V_m \sin \omega t$. The circuit is shown in the Fig. 7.4.

Pure inductance has zero ohmic resistance. Its internal resistance is zero. The coil has pure inductance of L henries (H).

When alternating current 'i' flows through inductance 'L', it sets up an alternating magnetic field around the inductance. This changing flux links the coil and due to self inductance, e.m.f. gets induced in the coil. This e.m.f. opposes the applied voltage.

The self induced e.m.f. in the coil is given by,

Self induced e.m.f., $e = -L\frac{di}{dt}$

At all instants, applied voltage, V is equal and opposite to the self induced e.m.f., e

$$\therefore \quad v = -e = -\left(-L\frac{di}{dt}\right)$$

$$\therefore \quad v = L\frac{di}{dt} \quad \text{i.e. } V_m \sin \omega t = L\frac{di}{dt}$$

$$\therefore \quad di = \frac{V_m}{L} \sin \omega t \, dt$$

$$\therefore \quad i = \int di = \int \frac{V_m}{L} \sin \omega t \, dt = \frac{V_m}{L}\left(\frac{-\cos \omega t}{\omega}\right)$$

$$= -\frac{V_m}{\omega L} \sin\left(\frac{\pi}{2} - \omega t\right) \quad \text{as } \cos \omega t = \sin\left(\frac{\pi}{2} - \omega t\right)$$

$$\therefore \quad i = \frac{V_m}{\omega L} \sin\left(\omega t - \frac{\pi}{2}\right) \quad \text{as } \sin\left(\frac{\pi}{2} - \omega t\right) = -\sin\left(\omega t - \frac{\pi}{2}\right)$$

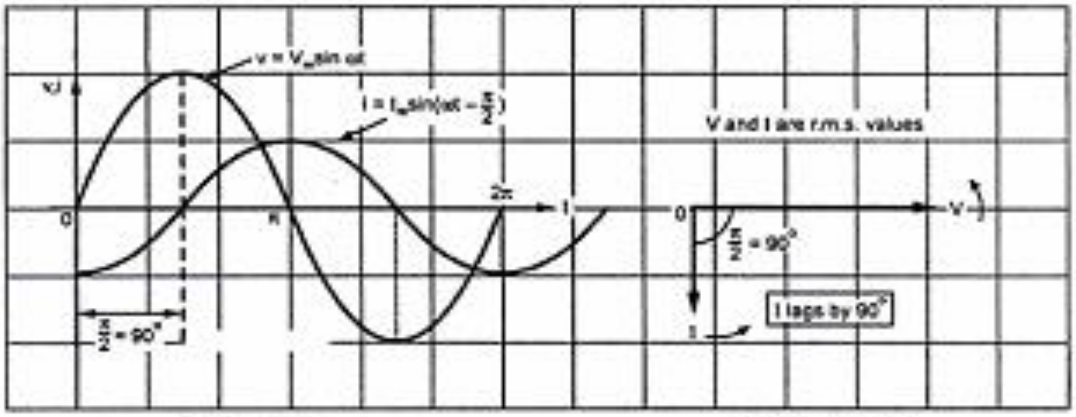
$$\therefore \quad \boxed{i = I_m \sin\left(\omega t - \frac{\pi}{2}\right)}$$

Where $I_m = \frac{V_m}{\omega L} = \frac{V_m}{X_L}$

Where $\boxed{X_L = \omega L = 2 \pi f L \ \Omega}$

The above equation clearly shows that the current is purely sinusoidal and having phase angle of $-\frac{\pi}{2}$ radians i.e. $-90°$. This means that the current lags voltage applied by 90°. The negative sign indicates lagging nature of the current. If current is assumed as a reference, we can say that the voltage across inductance leads the current passing through the inductance by 90°.

The Fig. 7.5 shows the waveforms and the corresponding phasor diagram.



(a) Waveforms (b) Phasor diagram

Fig. 7.5 A.C. through purely inductive circuit

7.3.1 Concept of Inductive Reactance

We have seen that in purely inductive circuit,

$$I_m = \frac{V_m}{X_L}$$

where $\boxed{X_L = \omega L = 2\pi f L \, \Omega}$

The term, X_L, is called Inductive Reactance and is measured in ohms.

So, inductive reactance is defined as the opposition offered by the inductance of a circuit to the flow of an alternating sinusoidal current.

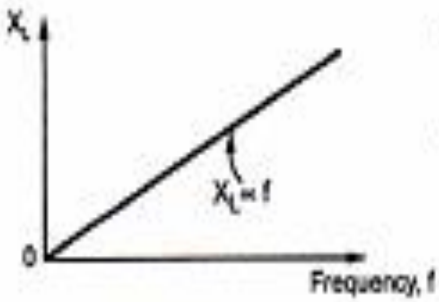


Fig. 7.6 X_L Vs f

It is measured in ohms and it depends on the frequency of the applied voltage.

The inductive reactance is directly proportional to the frequency for constant L.

$X_L \propto f$, for constant L

So, graph of X_L Vs f is a straight line passing through the origin as shown in the Fig. 7.6.

> **Key Point** : *If frequency is zero, which is so for d.c. voltage, the inductive reactance is zero. Therefore, it is said that the inductance offers zero reactance for the d.c. or steady current.*

7.3.2 Power

The expression for the instantaneous power can be obtained by taking the product of instantaneous voltage and current.

$$\therefore \quad P = v \times i = V_m \sin \omega t \times I_m \sin\left(\omega t - \frac{\pi}{2}\right)$$

$$= -V_m I_m \sin(\omega t)\cos(\omega t) \quad \text{as } \sin\left(\omega t - \frac{\pi}{2}\right) = -\cos \omega t$$

$$\therefore \quad \boxed{P = -\frac{V_m I_m}{2}\sin(2\omega t)} \quad \text{as } 2 \sin \omega t \cos \omega t = \sin 2\omega t$$

Key Point : *This power curve is a sine curve of frequency double than that of applied voltage.*

The average value of sine curve over a complete cycle is always zero.

$$P_{av} = \int_0^{2\pi} -\frac{V_m I_m}{2}\sin(2\omega t)\, d(\omega t) = 0$$

The Fig. 7.7 shows voltage, current and power waveforms.

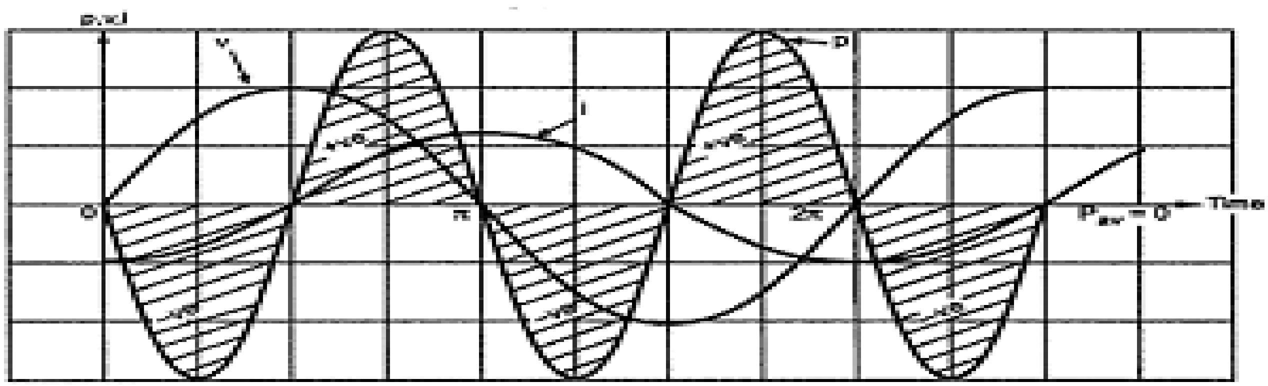


Fig. 7.7 Waveforms of voltage, current and power

It can be observed from it that when power curve is positive, energy gets stored in the magnetic field established due to the increasing current while during negative power curve, this power is returned back to the supply.

The areas of positive loop and negative loop are exactly same and hence, average power consumption is zero.

Key Point : *Pure inductance never consumes power.*

7.4 A.C. through Pure Capacitance

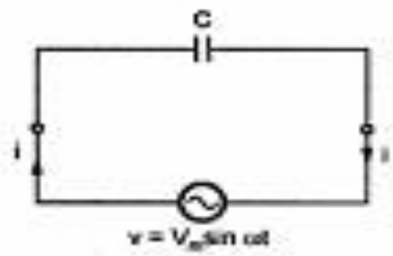


Fig. 7.8 Purely capacitive circuit

Consider a simple circuit consisting of a pure capacitor of C– farads, connected across a voltage given by the equation, $v = V_m \sin \omega t$. The circuit is shown in the Fig. 7.8.

The current i charges the capacitor C. The instantaneous charge 'q' on the plates of the capacitor is given by,

$$q = C v$$

$$\therefore \quad q = C V_m \sin \omega t$$

Now, current is rate of flow of charge.

$$\therefore \qquad i = \frac{dq}{dt} = \frac{d}{dt}(C V_m \sin \omega t)$$

$$\therefore \qquad i = C V_m \frac{d}{dt}(\sin \omega t) = C V_m \omega \cos \omega t$$

$$\therefore \qquad i = \frac{V_m}{\left(\frac{1}{\omega C}\right)} \sin\left(\omega t + \frac{\pi}{2}\right)$$

$$\therefore \qquad i = I_m \sin\left(\omega t + \frac{\pi}{2}\right)$$

where $\boxed{I_m = \frac{V_m}{X_C}}$

where $\boxed{X_C = \frac{1}{\omega C} = \frac{1}{2 \pi f C} \quad \Omega}$

The above equation clearly shows that the current is purely sinusoidal and having phase angle of $+\frac{\pi}{2}$ radians i.e. $+ 90°$.

This means **current leads voltage applied by 90°**. The positive sign indicates leading nature of the current. If current is assumed reference, we can say that voltage across capacitor lags the current passing through the capacitor by 90°.

The Fig. 7.9 shows waveforms of voltage and current and the corresponding phasor diagram. The current waveform starts earlier by 90° in comparison with voltage waveform. When voltage is zero, the current has positive maximum value.

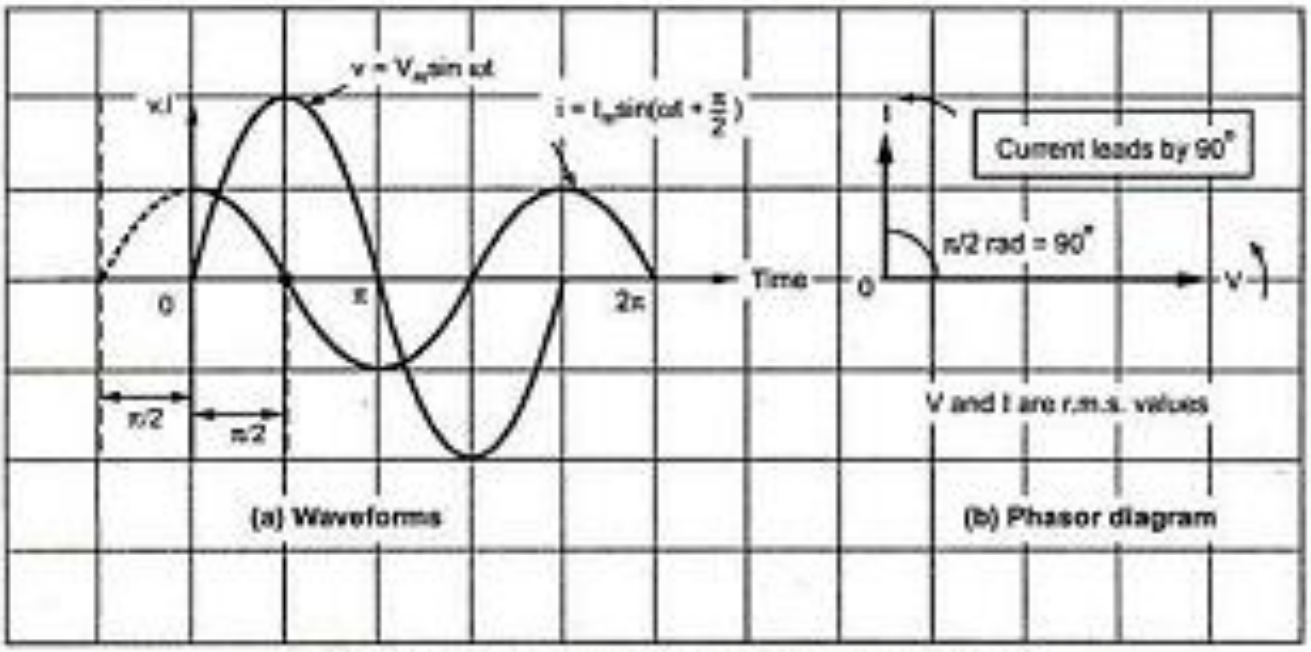


Fig. 7.9 A.C. through purely capacitive circuit

Key Point : *In purely capacitive circuit, current leads voltage by 90°.*

7.4.1 Concept of Capacitive Reactance

We have seen while expressing current equation in the standard form that,

$$I_m = \frac{V_m}{X_C} \quad \text{and} \quad X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}\,\Omega$$

The term X_C is called **Capacitive Reactance** and is measured in ohms.

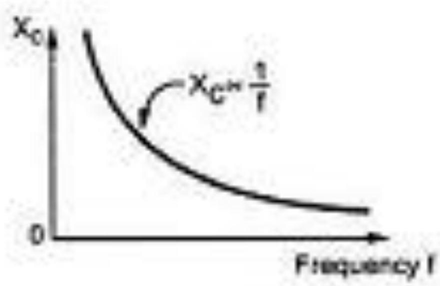


Fig. 7.10 X_C Vs f

So, **capacitive reactance** is defined as the opposition offered by the capacitance of a circuit to the flow of an alternating sinusoidal current.

X_C is measured in ohms and it depends on the frequency of the applied voltage.

The capacitive reactance is inversely proportional to the frequency for constant C.

$$X_C \propto \frac{1}{f} \quad \text{for constant C}$$

The graph of X_C Vs f is a rectangular hyperbola as shown in Fig. 7.10.

Key Point : *If the frequency is zero, which is so for d.c. voltage, the capacitive reactance is infinite. Therefore, it is said that the capacitance offers open circuit to the d.c. or it blocks d.c.*

7.5.1 Impedance

Impedance is defined as the opposition of circuit to flow of alternating current. It is denoted by Z and its unit is ohms.

For the R-L series circuit, it can be observed from the phasor diagram that the current lags behind the applied voltage by an angle ϕ. From the voltage triangle, we can write,

$$\tan\phi = \frac{V_L}{V_R} = \frac{X_L}{R}, \quad \cos\phi = \frac{V_R}{V} = \frac{R}{Z}, \quad \sin\phi = \frac{V_L}{V} = \frac{X_L}{Z}$$

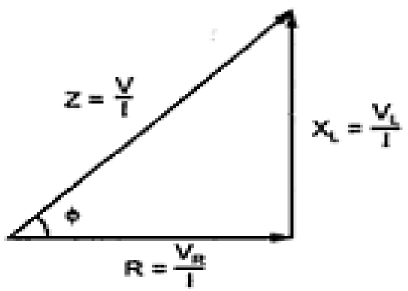


Fig. 7.15 Impedance triangle

If all the sides of the voltage triangle are divided by current, we get a triangle called impedance triangle as shown in the Fig. 7.15.

Sides of this triangle are resistance R, inductive reactance X_L and an impedance Z.

From this impedance triangle, we can see that the X component of impedance is R and is given by,

$$R = Z\cos\phi$$

and Y component of impedance is X_L and is given by,

$$X_L = Z\sin\phi$$

In rectangular form the impedance is denoted as,

$$\boxed{Z = R + jX_L \quad \Omega}$$

While in polar form, it is denoted as,

where

$$\boxed{\begin{aligned} Z &= |Z| \angle\phi \quad \Omega \\ |Z| &= \sqrt{R^2 + X_L^2}, \quad \phi = \tan^{-1}\left[\frac{X_L}{R}\right] \end{aligned}}$$

7.5.2 Power and Power Triangle

The expression for the current in the series R-L circuit is,

$$i = I_m \sin(\omega t - \phi) \text{ as current lags voltage.}$$

The power is product of instantaneous values of voltage and current,

$$\therefore \quad P = v \times i = V_m \sin \omega t \times I_m \sin(\omega t - \phi) = V_m I_m [\sin(\omega t) \cdot \sin(\omega t - \phi)]$$

$$= V_m I_m \left[\frac{\cos(\phi) - \cos(2\omega t - \phi)}{2}\right] = \frac{V_m I_m}{2} \cos\phi - \frac{V_m I_m}{2} \cos(2\omega t - \phi)$$

Now, the second term is cosine term whose average value over a cycle is zero. Hence, average power consumed is,

$$P_{av} = \frac{V_m I_m}{2} \cos\phi = \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}} \cos\phi$$

$$\therefore \quad \boxed{P = V I \cos\phi \quad \text{watts}} \quad \text{where V and I are r.m.s. values}$$

If we multiply voltage equation by current I, we get the power equation.

$$\overline{VI} = \overline{V_R I} + \overline{V_L I}$$

$$\therefore \quad \overline{VI} = \overline{V \cos\phi I} + \overline{V \sin\phi I}$$

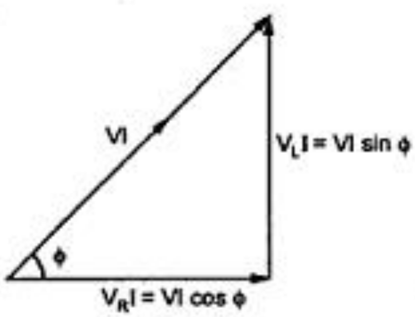


Fig. 7.16 Power triangle

From this equation, power triangle can be obtained as shown in the Fig. 7.16.

So, three sides of this triangle are,

1) VI, 2) VI cos ϕ 3) VI sin ϕ

These three terms can be defined as below.

7.5.3 Apparent Power (S)

It is defined as the product of r.m.s. value of voltage (V) and current (I). It is denoted by S.

$$\therefore \quad \boxed{S = V I \quad \text{VA}}$$

It is measured in unit volt-amp (VA) or kilo volt-amp (kVA).

7.5.4 Real or True Power (P)

It is defined as the product of the applied voltage and the active component of the current.

It is real component of the apparent power. It is measured in unit watts (W) or kilowatts (kW).

$$\boxed{P = V I \cos\phi \quad \text{watts}}$$

7.5.5 Reactive Power (Q)

It is defined as product of the applied voltage and the reactive component of the current.

It is also defined as imaginary component of the apparent power. It is represented by 'Q' and it is measured in unit volt-amp reactive (VAR) or kilovolt-amp reactive (kVAR).

$$\boxed{Q = V I \sin\phi \quad \text{VAR}}$$

Apparent power,	$S = V I$	VA	
True power	$P = V I \cos\phi$	W (Average Power)	
Reactive power	$Q = V I \sin\phi$	VAR	

7.5.6 Power Factor (cos ϕ)

It is defined as factor by which the apparent power must be multiplied in order to obtain the true power.

It is the ratio of true power to apparent power.

$$\boxed{\text{Power factor} = \frac{\text{True Power}}{\text{Apparent Power}} = \frac{V I \cos\phi}{V I} = \cos\phi}$$

The numerical value of cosine of the phase angle between the applied voltage and the current drawn from the supply voltage gives the power factor. It cannot be greater than 1.

It is also defined as the ratio of resistance to the impedance.

$$\boxed{\cos\phi = \frac{R}{Z}}$$

Key Point: *The nature of power factor is always determined by position of current with respect to the voltage.*

If current lags voltage power factor is said to be lagging. If current leads voltage power factor is said to be leading.

So, for pure inductance, the power factor is cos (90°) i.e. zero lagging while for pure capacitance, the power factor is cos (90°) i.e. zero but leading. For purely resistive circuit voltage and current are in phase i.e. $\phi = 0$. Therefore, power factor is cos (0°) = 1. Such circuit is called unity power factor circuit.

$$\boxed{\text{Power factor} = \cos\phi}$$

ϕ is the angle between supply voltage and current.

Key Point: *Nature of power factor always tells position of current with respect to voltage.*

7.6 A.C. through Series R-C Circuit

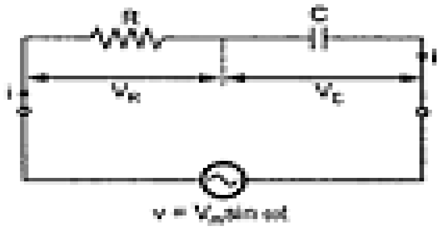


Fig. 7.19 Series R-C circuit

Consider a circuit consisting of pure resistance R-ohms and connected in series with a pure capacitor of C-farads as shown in the Fig. 7.19.

The series combination is connected across a.c. supply given by

$$v = V_m \sin \omega t$$

Circuit draws a current I, then there are two voltage drops,

a) Drop across pure resistance $V_R = I \times R$

b) Drop across pure capacitance $V_C = I \times X_C$

Where $\quad X_C = \dfrac{1}{2\pi f C}$ and I, V_R, V_C are the r.m.s. values

The Kirchhoff's voltage law can be applied to get,

$$V = \overline{V_R} + \overline{V_C} \qquad \text{... (Phasor Addition)}$$

$$\therefore \quad \overline{V} = \overline{IR} + \overline{IX_C}$$

Let us draw the phasor diagram. Current I is taken as reference as it is common to both the elements.

Following are the steps to draw the phasor diagram :

1) Take current as reference phasor.
2) In case of resistance, voltage and current are in phase. So, V_R will be along current phasor.
3) In case of pure capacitance, current leads voltage by 90° i.e. voltage lags current by 90° so V_C is shown downwards i.e. lagging current by 90°.
4) The supply voltage being vector sum of these two voltages V_C and V_R obtained by completing parallelogram.

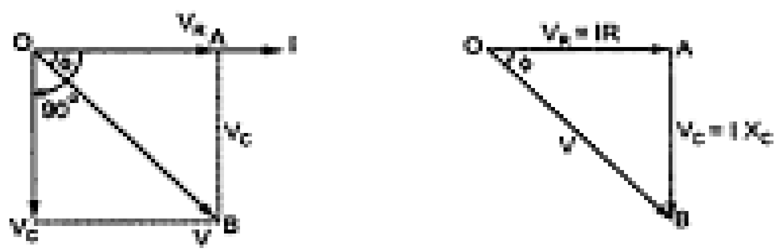


Fig. 7.20 Phasor diagram and voltage triangle

From the voltage triangles,

$$V = \sqrt{(V_R)^2 + (V_C)^2} = \sqrt{(IR)^2 + (I\,X_C)^2} = I\sqrt{(R)^2 + (X_C)^2}$$

$$\therefore \quad V = I\,Z$$

Where $\boxed{Z = \sqrt{(R)^2 + (X_C)^2}}$ is the impedance of the circuit.

7.6.1 Impedance

Similar to R-L series circuit, in this case also, the impedance is nothing but opposition to the flow of alternating current. It is measured in ohms given by $Z = \sqrt{(R)^2 + (X_C)^2}$ where $X_C = \dfrac{1}{2\pi f C}\,\Omega$ called capacitive reactance.

In R-C series circuit, current leads voltage by angle ϕ or supply voltage V lags current I by angle ϕ as shown in the phasor diagram in Fig. 7.20.

From voltage triangle, we can write,

$$\tan\phi = \frac{V_C}{V_R} = \frac{X_C}{R}, \quad \cos\phi = \frac{V_R}{V} = \frac{R}{Z}, \quad \sin\phi = \frac{V_C}{V} = \frac{X_C}{Z}$$

If all the sides of the voltage triangle are divided by the current, we get a triangle called **impedance triangle.**

Two sides of the triangle are 'R' and 'X_C' and the third side is impedance 'Z'.

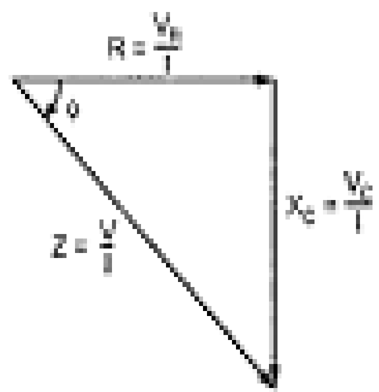


Fig. 7.21 Impedance triangle

The X component of impedance is R and is given by

$$R = Z\cos\phi$$

and Y component of impedance is X_C and is given by

$$X_C = Z\sin\phi$$

But, as direction of the X_C is the negative Y direction, the rectangular form of the impedance is denoted as,

$$\boxed{Z = R - j\,X_C\ \Omega}$$

While in polar form, it is denoted as,

$$\boxed{Z = |Z| \angle -\phi\ \Omega}$$

$$Z = R - j\,X_C = |Z| \angle -\phi$$

where $\quad |Z| = \sqrt{R^2 + X_C^2}, \ \phi = \tan^{-1}\left[\frac{-X_C}{R}\right]$

Key Point: *Thus ϕ is negative for capacitive impedance.*

7.6.2 Power and Power Triangle

The current leads voltage by angle ϕ, hence its expression is,

$$i = I_m \sin(\omega t + \phi) \text{ as current leads voltage}$$

The power is the product of instantaneous values of voltage and current.

$$\therefore \quad P = v \times i = V_m \sin \omega t \times I_m \sin(\omega t + \phi)$$

$$= V_m I_m [\sin(\omega t) \cdot \sin(\omega t + \phi)]$$

$$= V_m I_m \left[\frac{\cos(-\phi) - \cos(2\omega t + \phi)}{2}\right]$$

$$= \frac{V_m I_m \cos\phi}{2} - \frac{V_m I_m}{2}\cos(2\omega t + \phi) \qquad \text{as } \cos(-\phi) = \cos\phi$$

Now, second term is cosine term whose average value over a cycle is zero. Hence, average power consumed by the circuit is,

$$P_{av} = \frac{V_m I_m}{2}\cos\phi = \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}}\cos\phi$$

$$\therefore \quad \boxed{P = V I \cos\phi \text{ watts}} \quad \text{where V and I are r.m.s. values}$$

If we multiply voltage equation by current I, we get the power equation,

$$\overline{VI} = \overline{V_R I} + \overline{V_C I}$$

$$\therefore \quad \overline{VI} = \overline{VI\cos\phi} + \overline{VI\sin\phi}$$

Hence, the power triangle can be shown as in the Fig. 7.22.

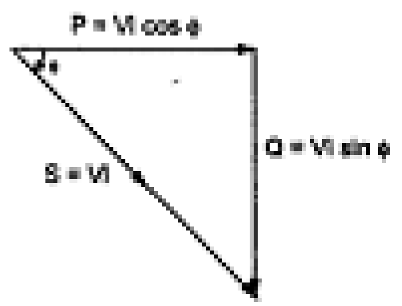


Fig. 7.22

Thus, the various powers are,

Apparent power,	$S = V I$ VA
True or average power,	$P = V I \cos\phi$ W
Reactive power,	$Q = V I \sin\phi$ VAR

Remember that, X_L term appears positive in Z.

$$Z = R + j X_L = |Z| \angle \phi \qquad \phi \text{ is positive for inductive Z}$$

While X_C term appears negative in Z.

$$Z = R - j X_C = |Z| \angle -\phi \qquad \phi \text{ is negative for capacitive Z}$$

For any single phase a.c. circuit, the average power is given by,

$$P = V I \cos\phi \quad \text{watts}$$

Where V, I are r.m.s. values

$\cos\phi$ = Power factor of circuit

$\cos\phi$ is lagging for inductive circuit and $\cos\phi$ is leading for capacitive circuit.

7.7 A.C. through Series R-L-C Circuit

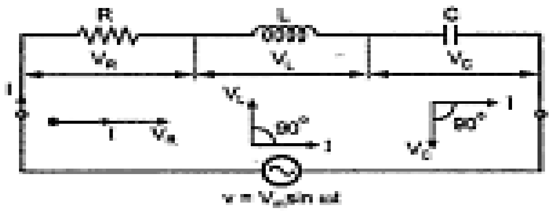


Fig. 7.25 R-L-C series circuit

Consider a circuit consisting of resistance R ohms pure inductance L henries and capacitance C farads connected in series with each other across a.c. supply. The circuit is shown in the Fig. 7.25.

The a.c. supply is given by,

$v = V_m \sin \omega t$. The circuit draws a current I. Due to current I, there are different voltage drops across R, L and C which are given by,

a) Drop across resistance R is $V_R = I R$

b) Drop across inductance L is $V_L = I X_L$

c) Drop across capacitance C is $V_C = I X_C$

The values of I, V_R, V_L and V_C are r.m.s. values

The characteristics of three drops are,

a) V_R is in phase with current I.

b) V_L leads current I by 90°.

c) V_C lags current I by 90°.

According to Kirchhoff's laws, we can write,

$$\bar{V} = \bar{V}_R + \bar{V}_L + \bar{V}_C \qquad \text{... Phasor addition}$$

Let us see the phasor diagram. Current I is taken as reference as it is common to all the elements.

Following are the steps to draw the phasor diagram :

1) Take current as reference. 2) V_R is in phase with I.

3) V_L leads current I by 90°. 4) V_C lags current I by 90°.

5) Obtain the resultant of V_L and V_C. Both V_L and V_C are in phase opposition (180° out of phase).

6) Add that with V_R by law of parallelogram to get the supply voltage.

The phasor diagram depends on the conditions of the magnitudes of V_L and V_C which ultimately depends on the values of X_L and X_C. Let us consider the different cases.

7.7.1 $X_L > X_C$

When $X_L > X_C$, obviously, I X_L i.e. V_L is greater than I X_C i.e. V_C. So, resultant of V_L and V_C will be directed towards V_L i.e. leading current I. Current I will lag the resultant of V_L and V_C i.e. $(V_L - V_C)$.

The circuit is said to be inductive in nature. The phasor sum of V_R and $(V_L - V_C)$ gives the resultant supply voltage, V. This is shown in the Fig. 7.26.

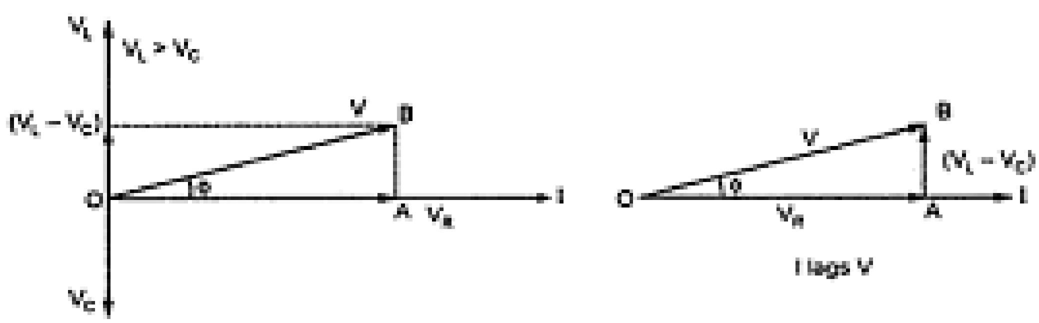


Fig. 7.26 Phasor diagram and voltage triangle for $X_L > X_C$

From the voltage triangle, $V = \sqrt{(V_R)^2 + (V_L - V_C)^2} = \sqrt{(I R)^2 + (I X_L - I X_C)^2}$

$$= I\sqrt{(R)^2 + (X_L - X_C)^2}$$

$$\therefore \qquad V = I Z$$

∴ V = I Z

Where Z = R

7.7.4 Impedance

In general, for RLC series circuit impedance is given by,

$$Z = R + jX$$

Where $X = X_L - X_C$ = total reactance of circuit

If $X_L > X_C$, X is positive and circuit is inductive.

If $X_L < X_C$, X is negative and circuit is capacitive.

If $X_L = X_C$, X is zero and circuit is purely resistive.

$$\tan\phi = \left[\frac{X_L - X_C}{R}\right],\ \cos\phi = \frac{R}{Z} \text{ and } Z = \sqrt{R^2 + (X_L - X_C)^2}$$

7.7.5 Impedance Triangle

The impedance is expressed as,

$$Z = R + jX \quad \text{where} \quad X = X_L - X_C$$

For $X_L > X_C$, ϕ is positive and the impedance triangle is as shown in the Fig. 7.29 (a).

For $X_L < X_C$, $X_L - X_C$ is negative, so ϕ is negative and the impedance triangle is as shown in Fig. 7.29 (b).

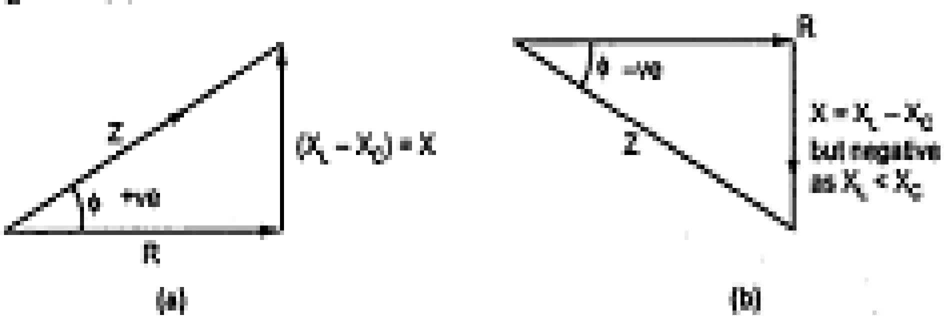


Fig. 7.29 Impedance triangles

In both the cases, $R = Z\cos\phi$ and $X = Z\sin\phi$

7.7.6 Power and Power Triangle

The average power consumed by the circuit is,

P_{av} = Average power consumed by R + Average power consumed by L + Average power consumed by C

But, pure L and C never consume any power.

$\therefore \quad P_{av}$ = Power taken by R $= I^2 R = I(IR) = IV_R$

But, $\quad V_R = V\cos\phi$ in both the cases

UNIT-III

Faraday’s Laws of Electromagnetic Induction

Faraday’s Laws of Electromagnetic Induction consists of two laws. The first law describes the induction of emf in a conductor and the second law quantifies the emf produced in the conductor. In the next few sections, let us learn these laws in detail.

1st law: Whenever a conductor is placed in a varying magnetic field, an electromotive force is induced. If the conductor circuit is closed, a current is induced which is called induced current.

2nd Law: The induced emf in a coil is equal to the rate of change of flux linkage.

$$E = -N\frac{d\phi}{dt}$$

Self Induced EMF :

It is defined as the emf induced in the coil due to increase or decrease of the current in the same coil. If the current is constant no. emf is induced. When a current is passed to a circuit due to self induced emf the flow of current in the circuit is opposed .

Mutually induced emf:

Coil ‘B’ is connected to galvanometer. coil ‘A’ is connected to a cell. The two coils are placed close together. The coil connected to a supply is called primary coil A. The other coil ‘B’ is called secondary coil. The coil in which emf is induced by mutual induction is called secondary coil. When current through coil ‘A’ is established by closing switch ‘S’ then its magnetic field is setup which partly links with or threads through the coil ‘B’. As current through ‘A’ is changed the flux linked with ‘B’ is also changed. Hence mutually induced emf is produced in ‘B’ whose magnitude is given by faraday’s law and direction by lenz’s law. The property of inducing emf in one coil due to change of current in other coil placed near the former is called mutual induction and this property is used in Transformers and Induction coils.

TRANSFORMERS

A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled conductors—the transformer's coils. A varying current in the first or primary winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force (EMF), or "voltage", in the secondary winding. This effect is called inductive coupling.

Discovery

Faraday's experiment with induction between coils of wire

The phenomenon of electromagnetic induction was discovered independently by Michael Faraday and Joseph Henry in 1831. However, Faraday was the first to publish the results of his experiments and thus receive credit for the discovery. The relationship between electromotive force (EMF) or "voltage" and magnetic flux was formalized in an equation now referred to as "Faraday's law of induction":

$$|\mathcal{E}| = \left|\frac{d\Phi_B}{dt}\right|$$

Where $|\mathcal{E}|$ is the magnitude of the EMF in volts and Φ_B is the magnetic flux through the circuit in Weber's. Faraday performed the first experiments on induction between coils of wire, including winding a pair of coils around an iron ring, thus creating the first toroidal closed-core transformer.

WORKING PRINCIPLE OF TRANSFORMER:

Introduction

The main advantage of alternating currents over direct current is that, the alternating currents can be easily transferable from low voltage to high voltage or high voltage to low. Alternating voltages can be raised or lowered as per requirements in the different stages of electrical network as generation, transmission, distribution and utilization. This is possible with a static device called transformer. The transformer works on the principle of mutual induction. It transfer an electric energy from one circuit to other when there is no electrical connection between the two circuits. Thus we can define transformer as below:

Key point: The transformer is a static piece of apparatus by means of which an electrical power is transformed from one alternating current circuit to another with the desired change in voltage and current, without any change in the frequency.

The use of transformers in transmission system is shown in the Fig 1.1.

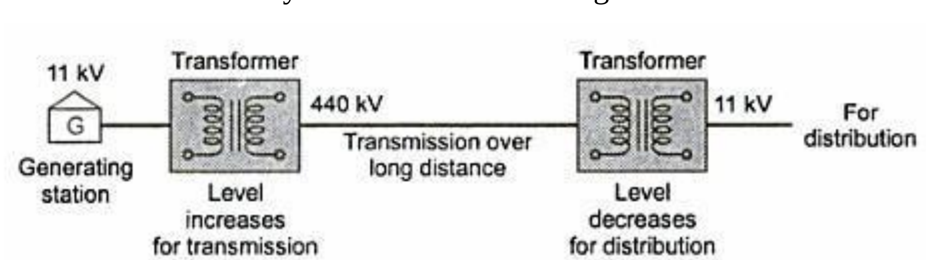
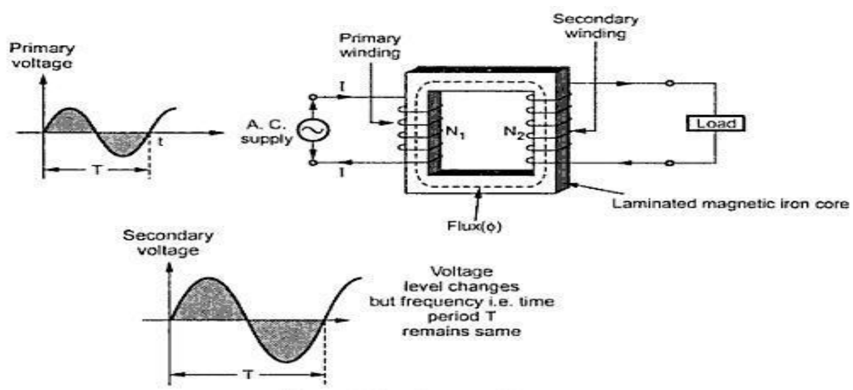


Fig. 1.1 Use of transformer in transmission system

PRINCIPLE OF WORKING

The principle of mutual induction states that when two coils are inductively coupled and if current in one coil is changed uniformly then an e.m.f. gets induced in the other coil. This e.m.f can drive a current, when a closed path is provided to it. The transformer works on the same principle. In its elementary form, it consists of two inductive coils which are electrically separated but linked through a common magnetic circuit. The two coils have high mutual inductance. The basic transformer is shown in the Fig 1.2.

One of the two coils is connected to source of alternating voltage. This coil in which electrical energy is fed with the help of source called primary winding (P). The other winding is connected to load. The electrical energy transformed to this winding is drawn out to the load.



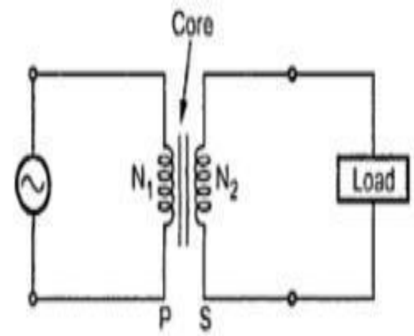


Fig.1.2 Basic transformer Fig 1.3 Symbolic representation

This winding is called secondary winding (S). The primary winding has N_1 number of turns while the secondary winding has N_2 number of turns. Symbolically the transformer is indicated as shown in the Fig 1.3.

When primary winding is excited by an alternating voltage, it circulates an alternating current. This current produces an alternating flux (Φ) which completes its path through common magnetic core as shown dotted in the Fig 1.2. Thus an alternating flux links with the secondary winding. As the flux is alternating, according to Faraday's law of an electromagnetic induction, mutually induced e.m.f. gets developed in the secondary winding. If now load is connected to the secondary winding, this e.m.f. drives a current through it.

Thus through there is no electrical contact between the two windings, an electrical energy gets transferred from primary to the secondary.

Key point: The frequency of the mutual induced e.m.f. is same as that of the alternating source which is supplying energy to the primary winding.

CONSTRUCTION OF TRANSFORMER:

There are two basic parts of a transformer (i) Magnetic Core (ii) Winding or Coils.

The core of the transformer is either square or rectangular in size. It is further divided into two parts. The vertical position on which coils are wound is called limb while the top and bottom horizontal portion is called yoke of the core. These parts are shown in the Fig.1 (a).

Core is made up of lamination. Because of laminated type of construction, eddy current losses get minimized. Generally high grade silicon steel laminations (0.3 to 0.5 mm thick) are used. These laminations are insulated from each other by using insulation like varnish. All laminations are varnished. Laminations are overlapped so that to avoid the air gap at joints. For this generally 'L' shaped or 'I' shaped laminations are used which are shown in the Fig 1(b).

Fig. 1 Construction of transformer

The cross-section of the limb depends on the type of coil to be used either circular or rectangular. The different cross-section of limbs, practically used are shown in the Fig. 2.

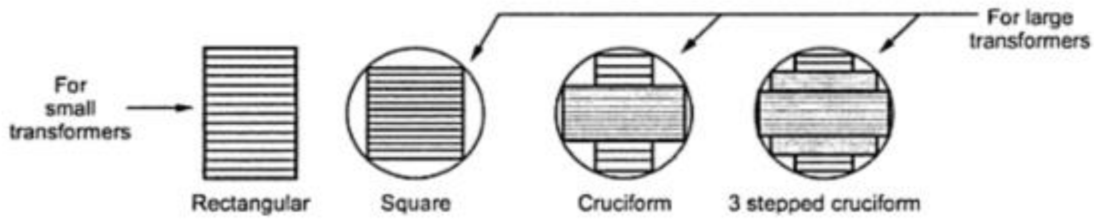


Fig. 2 Different cross-sections

The various types of depending on the construction of core used for the single phase transformers are,

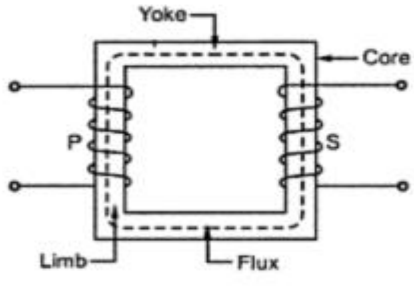
1. Core type 2. Shell type and 3. Berry type

1. Core Type Transformer

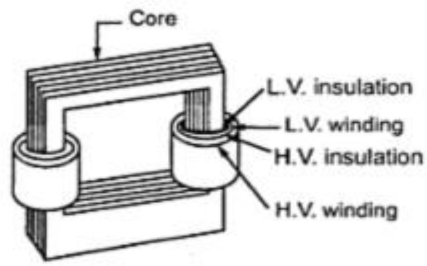
It has a single magnetic circuit. The core rectangular is having two limbs. The winding encircles the core. The coils used are of cylindrical type. As mentioned earlier, the coils are wound in helical layers with different layers insulated from each other by paper or mica. Both the coils are placed on both the limbs. The low voltage coil is placed inside near the core while high voltage coil surrounds the low voltage coil. Core is made up of large number of thin laminations.

As the windings are uniformly distributed over the two limbs, the natural cooling is more effective. The coils can be easily removed by removing the laminations of the top yoke, for maintenance.

The Fig. 1(a) shows the schematic representation of the core type transformer while the Fig 1(b) shows the view of actual construction of the core type transformer.



(a) Representation



(b) Construction

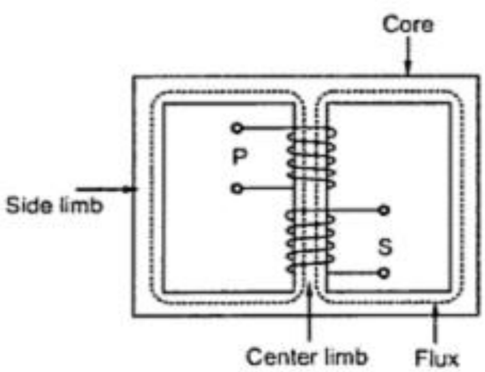
Fig. 1 Core type transformer

2. Shell Type Transformer

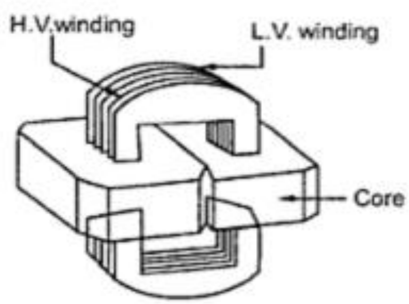
It has a double magnetic circuit. The core has three limbs. Both the windings are placed on the central limb. The core encircles most part of the windings. The coils used are generally multilayer disc type or sandwich coils. As mentioned earlier, each high voltage coil is in between tow low voltage coils and low voltage coils are nearest to top and bottom of the yokes.

The core is laminated. While arranging the laminations of the core, the care is taken that all the joints at alternate layers are staggered. This is done to avoid narrow air gap at the joint, right through the cross-section of the core. Such joints are called over lapped or imbricated joint. Generally for very high voltage transformers, the shell type construction is preferred. As the windings are surrounded by the core, the natural cooling does not exist. For removing any winding for maintenance, a large number of laminations are required to be removed.

The Fig. 2(a) shows the schematic representation while the Fig. 2(b) shows the cut-away view of the construction of the shell type transformer.



(a) Representation



(b) Construction

Fig 2 Shell type transformer

Comparison of Core and Shell Type Transformers

Sr. No.	Core Type	Shell Type
1.	The winding encircles the core.	The core encircles most part of the windings.
2.	The cylindrical type of coils are used.	Generally, multilayer disc type or sandwich coils are used.
3.	As windings are distributed, the natural cooling is more effective.	As windings are surrounded by the core, the natural cooling does not exist.
4.	The coils can be easily removed from maintenance point of view.	For removing any winding for the maintenance, large number of laminations are required to be removed. This is difficult.
5.	The construction is preferred for low voltage transformers.	The construction is used for very high voltage transformers.
6.	It has a single magnetic circuit.	It has a double magnetic circuit.
7.	In a single phase type, the core has two limbs.	In a single phase type, the core has three limbs.

E.M.F EQUATION OF TRANSFORMER:

When the primary winding is excited by an alternating voltage V_1, it circulates alternating current, producing an alternating flux Φ. The primary winding has N_1 number of turns. The alternating flux Φ linking with the primary winding itself induces an e.m.f in it denoted as E_1. The flux links with secondary winding through the common magnetic core. It produces induced e.m.f. E_2 in the secondary winding. This is mutually induced e.m.f. Let us derive the equations for E_1 and E_2.

The primary winding is excited by purely sinusoidal alternating voltage. Hence the flux produced is also sinusoidal in nature having maximum value of Φ_m as show in the Fig. 1.

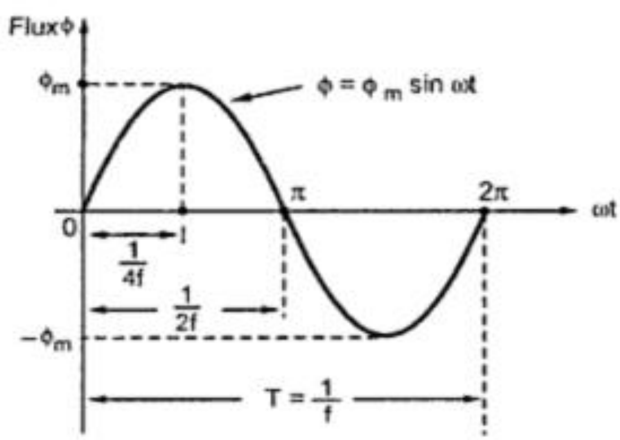


Fig. 1 Sinusoidal flux

The various quantities which affect the magnitude of the induced e.m.f. are:

Φ = Flux

Φ_m = Maximum value of flux

N_1 = Number of primary winding turns

N_2 = Number of secondary winding turns

f = Frequency of the supply voltage

E_1 = R.M.S. value of the primary induced e.m.f.

E_2 = R.M.S. value of the secondary induced e.m.f.

From Faraday's law of electromagnetic induction the voltage e.m.f. induced in each turn is proportional to the average rate of change of flux.

$\therefore$ average e.m.f. per turn = average rate of change of flux

$\therefore$ average e.m.f. per turn = $d\Phi/dt$

Now $d\Phi/dt$ = Change in flux/Time required for change in flux

Consider the 1/4 th cycle of the flux as shown in the Fig.1. Complete cycle gets completed in 1/f seconds. In 1/4 th time period, the change in flux is from 0 to Φ_m.

$\therefore$ $d\Phi/dt = (\Phi_m - 0)/(1/4f)$ as dt for 1/4 th time period is 1/4f seconds

$= 4 f \Phi_m$ Wb/sec

$\therefore$ Average e.m.f. per turn = $4 f \Phi_m$ volts

As is sinusoidal, the induced e.m.f. in each turn of both the windings is also sinusoidal in nature. For sinusoidal quantity,

From factor = R.M.S. value/Average value = 1.11

$\therefore$ R.M.S. value of induced e.m.f. per turn

$= 1.11 \times 4 f \Phi_m = 4.44 f \Phi_m$

There are number of primary turns hence the R.M.S value of induced e.m.f. of primary denoted as is E_1,

$E_1 = N_1 \times 4.44 f \Phi_m$ volts

While as there are number of secondary turns the R.M.S values of induced e.m.f. of secondary denoted is E_2 is,

$E_2 = N_2 \times 4.44 f \Phi_m$ volts

The expression of E_1 and E_2 are called e.m.f. equation of a transformer.

Thus e.m.f. equations are,

$E_1 = 4.44 f \Phi_m N_1$ volts ....(1)

$E_2 = 4.44 f \Phi_m N_2$ volts ....(2)

7.12 Exact Equivalent Circuit of a Loaded Transformer

Fig. (7.19) shows the exact equivalent circuit of a transformer on load. Here R_1 is the primary winding resistance and R_2 is the secondary winding resistance. Similarly, X_1 is the leakage reactance of primary winding and X_2 is the leakage reactance of the secondary winding. The parallel circuit $R_0 - X_0$ is the no-load equivalent circuit of the transformer. The resistance R_0 represents the core losses (hysteresis and eddy current losses) so that current I_W which supplies the core losses is shown passing through R_0. The inductive reactance X_0 represents a loss-free coil which passes the magnetizing current I_m. The phasor sum of I_W and I_m is the no-load current I_0 of the transformer.

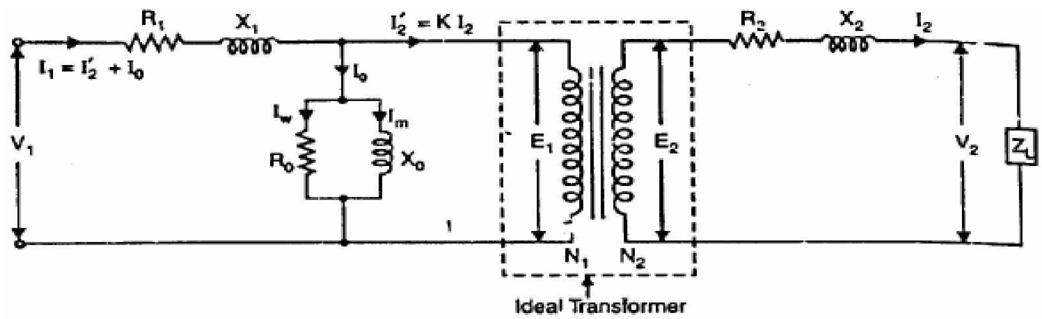


Fig. (7.19)

is composed of (a) magnetizing current (I_m) to create magnetic flux in the core and (b) the current I_W required to supply the core losses.

(ii) When the secondary circuit of a transformer is closed through some external load Z_L, the voltage E_2 induced in the secondary by mutual flux will produce a secondary current I_2. There will be $I_2 R_2$ and $I_2 X_2$ drops in the secondary winding so that load voltage V_2 will be less than E_2.

$$V_2 = E_2 - I_2(R_2 + j X_2) = E_2 - I_2 Z_2$$

(iii) When the transformer is loaded to carry the secondary current I_2, the primary current consists of two components:

(a) The no-load current I_0 to provide magnetizing current and the current required to supply the core losses.

(b) The primary current I'_2 (= K I_2) required to supply the load connected to the secondary.

$\therefore$ Total primary current $I_1 = I_0 + (-KI_2)$

(iv) Since the transformer in Fig. (7.19) in now ideal, the primary induced voltage E_1 can be calculated from the relation:

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

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

$$V_1 = -E_1 + I_1(R_1 + j X_1) = -E_1 + I_1 Z_1$$

or $$V_1 = -E_1 + I_1 Z_1$$

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

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

The following points may be noted from the equivalent circuit:

(i) When the transformer is on no-load (i.e., secondary terminals are open-circuited), there is no current in the secondary winding. However, the primary draws a small no-load current I_0. The no-load primary current I_0

7.24 Losses in a Transformer

The power losses in a transformer are of two types, namely;

1. Core or Iron losses
2. Copper losses

These losses appear in the form of heat and produce (i) an increase in temperature and (ii) a drop in efficiency.

1. Core or Iron losses (P_i)

These consist of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test.

$$\text{Hysteresis loss, } = k_h \; f \; B_m^{1.6} \quad \text{watts/m}^3$$

$$\text{Eddy current loss, } = k_e \; f^2 \; B_m^2 t^2 \qquad \text{watts/m}^3$$

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

$$\text{Iron or Core losses, } P_i = \text{Hysteresis loss} + \text{Eddy current loss}$$

$$= \text{Constant losses}$$

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

2. Copper losses

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

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

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

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

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

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

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

7.25 Efficiency of a Transformer

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

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

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

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

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

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

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

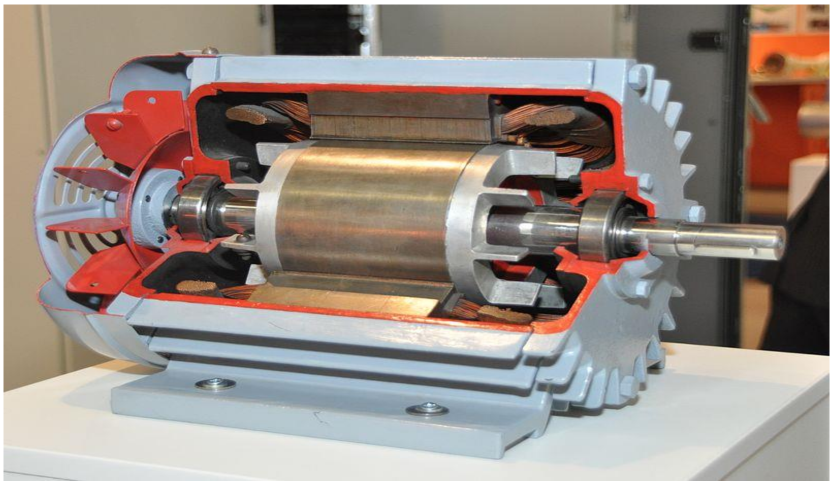
Due to these drawbacks, direct loading method is seldom used to determine the efficiency of a transformer. In practice, open-circuit and short-circuit tests are carried out to find the efficiency.

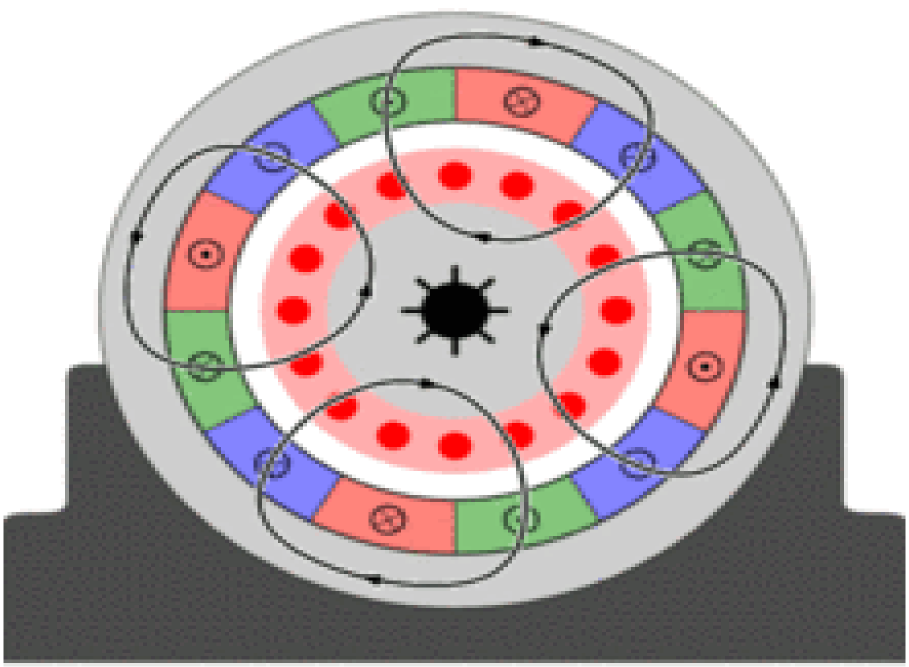
$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

The losses can be determined by transformer tests.

UNIT-IV

Electrical Machines





An induction or asynchronous motor is an AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. An induction motor therefore does not require mechanical commutation, separate-excitation or self-excitation for all or part of the energy transferred from stator to rotor, as in universal, DC and large synchronous motors. An induction motor's rotor can be either wound type or squirrel-cage type.

Three-phasesquirrel-cage induction motors are widely used in industrial drives because they are rugged, reliable and economical. Single-phase induction motors are used extensively for smaller loads, such as household appliances like fans. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed service. VFDs offer especially important energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications. Squirrel cage induction motors are very widely used in both fixed-speed and variable-frequency drive (VFD) applications. Variable voltage and variable frequency drives are also used in variable-speed service

Principles of operation

A three-phase power supply provides a rotating magnetic field in an induction moInherent slip - unequal rotation frequency of stator field and the rotor.

In both induction and synchronous motors, the AC power supplied to the motor's stator creates a magnetic field that rotates in time with the AC oscillations. Whereas a synchronous motor's rotor turns at the same rate as the stator field, an induction motor's rotor rotates at a slower speed than the stator field. The induction motor stator's magnetic field is therefore changing or rotating relative to the rotor. This induces an opposing current in the induction motor's rotor, in effect the motor's secondary winding, when the latter is short-circuited or closed through an external impedance.[22] The rotating magnetic flux induces currents in the windings of the rotor;[23] in a manner similar to currents induced in a transformer's secondary winding(s). The currents in the rotor windings in turn create magnetic fields in the rotor that react against the stator field. Due to Lenz's Law, the direction of the magnetic field created will be such as to oppose the change in current through the rotor windings. The cause of induced current in the rotor windings is the rotating stator magnetic field, so to oppose the change in rotor-winding currents the rotor will start to rotate in the direction of the rotating stator magnetic field. The rotor accelerates until the magnitude of induced rotor current and torque balances the applied load. Since rotation at synchronous speed would result in no induced rotor current, an induction motor always operates slower than synchronous speed. The difference, or "slip," between actual and synchronous speed varies from about 0.5 to 5.0% for standard Design B torque curve induction motors.[24] The induction machine's essential character is that it is created solely by induction instead of being separately excited as in synchronous or DC machines or being self-magnetized as in permanent magnet motors.[22]

For rotor currents to be induced, the speed of the physical rotor must be lower than that of the stator's rotating

magnetic field ( ); otherwise the magnetic field would not be moving relative to the rotor conductors and no currents would be induced. As the speed of the rotor drops below synchronous speed, the rotation rate of the magnetic field in the rotor increases, inducing more current in the windings and creating more torque. The ratio between the rotation rate of the magnetic field induced in the rotor and the rotation rate of the stator's rotating field is called slip. Under load, the speed drops and the slip increases enough to create sufficient torque to turn the load. For this reason, induction motors are sometimes referred to as asynchronous motors.[25] An induction motor can be used as an induction generator, or it can be unrolled to form a linear induction motor which can directly generate linear motion.

Synchronous speed

An AC motor's synchronous speed, is the rotation rate of the stator's magnetic field, which is expressed in revolutions per minute as (RPM), where is the motor supply's frequency in hertz and is the number of magnetic poles.[26][27] That is, for a six-pole three-phase motor with three pole-pairs set 120° apart, equals 6 and equals 1,000 RPM and 1,200 RPM respectively for 50 Hz and 60 Hz supply systems.

Slip

Typical torque curve as a function of slip, represented as 'g' here.Slipis defined as the difference between synchronous speed and operating speed, at the same frequency, expressed in rpm or in percent or ratio of synchronous speed. Thuswhere is stator electrical speed, is rotor mechanical speed.[9][28] Slip, which varies from zero at synchronous speed and 1 when the rotor is at rest, determines the motor's torque. Since the short-circuited rotor windings have small resistance, a small slip induces a large current in the rotor and produces large torque.[29] At full rated load, slip varies from more than 5% for small or special purpose motors to less than 1% for large motors.[30] These speed variations can cause load-sharing problems when differently sized motors are mechanically connected.[30] Various methods are available to reduce slip, VFDs often offering the best solution

DC Machines

1.1 Introduction

The study of the electrical engineering, basically involves the analysis of the energy transfer from one form to another. An electrical machine, deals with the energy transfer either from mechanical to electrical form or from electrical to mechanical form. This process is called **electromechanical energy conversion.**

An electrical machine which converts mechanical energy into an electrical energy is called an **electric generator**. While an electrical machine which converts an electrical energy into the mechanical energy is called an **electrical motor.**

Such electrical machines may be related to an electrical energy of an alternating type called **a.c. machines** or may be related to an electrical energy of direct type called **d.c. machines.**

The d.c. machines are classified as d.c. generators and d.c. motors. The construction of a d.c. machine basically remains same whether it is a generator or a motor. In this chapter constructional features of a d.c. machine, working principle and types of d.c. generator are discussed. But before beginning the study of the d.c. machines, it is necessary to revise the basic concepts of magnetism and electromagnetism.

1.7 Construction of a Practical D.C. Machine

As stated earlier, whether a machine is **d.c. generator or a motor** the construction basically remains the same as shown in the Fig. 1.14.

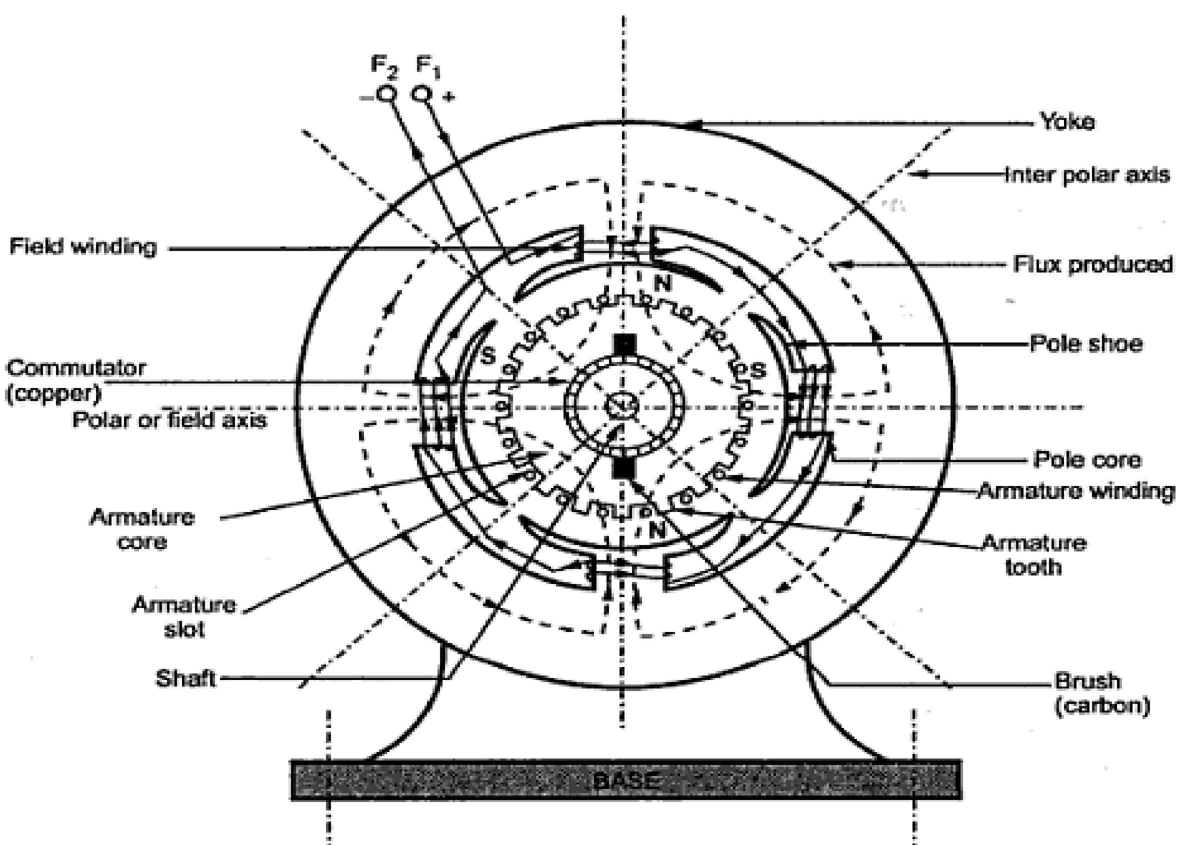


Fig. 1.14 A cross-section of typical d.c. machine

It consists of the following parts :

1.7.1 Yoke

a) Functions :

1. It serves the purpose of outermost cover of the d.c. machine. So that the insulating materials get protected from harmful atmospheric elements like moisture, dust and various gases like SO_2 , acidic fumes etc.

2. It provides mechanical support to the poles.

3. It forms a part of the magnetic circuit. It provides a path of low reluctance for magnetic flux. The low reluctance path is important to avoid wastage of power to provide same flux. Large current and hence the power is necessary if the path has high reluctance, to produce the same flux.

b) Choice of material : To provide low reluctance path, it must be made up of some magnetic material. It is prepared by using cast iron because it is cheapest. For large machines rolled steel, cast steel, silicon steel is used which provides high permeability i.e. low reluctance and gives good mechanical strength.

1.7.2 Poles

Each pole is divided into two parts namely, I) Pole core and II) Pole shoe.

This is shown in the Fig. 1.15.

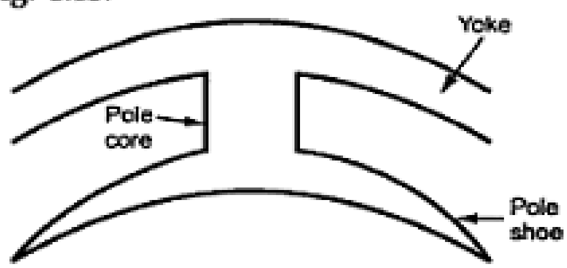


Fig. 1.15 Pole structure

a) Functions of pole core and pole shoe :

1. Pole core basically carries a field winding which is necessary to produce the flux.
2. It directs the flux produced through air gap to armature core, to the next pole.
3. Pole shoe enlarges the area of armature core to come across the flux, which is necessary to produce larger induced e.m.f. To achieve this, pole shoe has been given a particular shape.

b) Choice of material : It is made up of magnetic material like cast iron or cast steel.

As it requires a definite shape and size, laminated construction is used. The laminations of required size and shape are stamped together to get a pole which is then bolted to the yoke.

1.7.3 Field Winding (F1 - F2)

The field winding is wound on the pole core with a definite direction.

a) Functions : To carry current due to which pole core, on which the field winding is placed behaves as an electromagnet, producing necessary flux.

As it helps in producing the magnetic field i.e. exciting the pole as an electromagnet it is called **Field winding or Exciting winding.**

b) Choice of material : It has to carry current hence obviously made up of some conducting material. So aluminium or copper is the choice. But field coils are required to take any type of shape and bend about pole core and copper has good pliability i.e. it can bend easily. So copper is the proper choice.

> **Key Point :** *Field winding is divided into various coils called field coils. These are connected in series with each other and wound in such a direction around pole cores, such that alternate 'N' and 'S' poles are formed.*

By using right hand thumb rule for current carrying circular conductor, it can be easily determined that how a particular core is going to behave as 'N' or 'S' for a particular winding direction around it. The direction of winding and flux can be observed in the Fig. 1.10.

1.7.4 Armature

It is further divided into two parts namely,

I) Armature core and II) Armature winding

I) Armature core : Armature core is cylindrical in shape mounted on the shaft. It consists of slots on its periphery and the air ducts to permit the air flow through armature which serves cooling purpose.

a) Functions :

1. Armature core provides house for armature winding i.e. armature conductors.
2. To provide a path of low reluctance to the magnetic flux produced by the field winding.

b) Choice of material : As it has to provide a low reluctance path to the flux, it is made up of magnetic material like cast iron or cast steel.

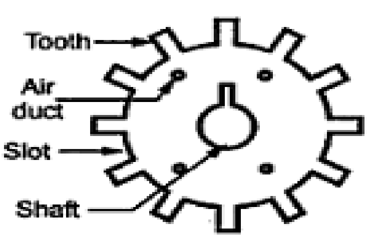


Fig. 1.16 Single circular lamination of armature core

It is made up of laminated construction to keep eddy current loss as low as possible. A single circular lamination used for the construction of the armature core is shown in the Fig. 1.16.

II) Armature winding : Armature winding is nothing but the interconnection of the armature conductors, placed in the slots provided on the armature core periphery. When the armature is rotated, in case of generator, magnetic flux gets cut by armature conductors and e.m.f. gets induced in them.

a) Functions :

1. Generation of e.m.f. takes place in the armature winding in case of generators.
2. To carry the current supplied in case of d.c. motors.
3. To do the useful work in the external circuit.

b) Choice of material : As armature winding carries entire current which depends on external load, it has to be made up of conducting material, which is copper.

Armature winding is generally former wound. The conductors are placed in the armature slots which are lined with tough insulating material.

1.7.5 Commutator

We have seen earlier that the basic nature of e.m.f. induced in the armature conductors is alternating. This needs rectification in case of d.c. generator, which is possible by a device called commutator.

a) Functions :

1. To facilitate the collection of current from the armature conductors.
2. To convert internally developed alternating e.m.f. to unidirectional (d.c.) e.m.f.
3. To produce unidirectional torque in case of motors.

b) Choice of material : As it collects current from armature, it is also made up of copper segments.

It is cylindrical in shape and is made up of wedge shaped segments of hard drawn, high conductivity copper. These segments are insulated from each other by thin layer of mica. Each commutator segment is connected to the armature conductor by means of copper lug or strip. This connection is shown in the Fig. 1.17.

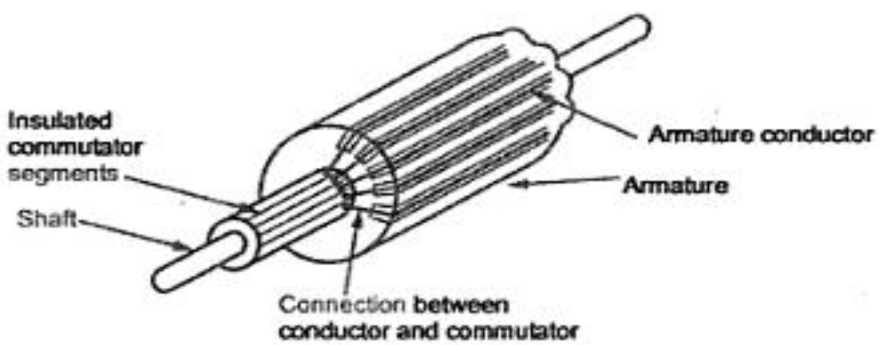


Fig. 1.17 Commutator

1.7.6 Brushes and Brush Gear

Brushes are stationary and resting on the surface of the commutator.

a) Function : To collect current from commutator and make it available to the stationary external circuit.

b) Choice of material : Brushes are normally made up of soft material like carbon.

Brushes are rectangular in shape. They are housed in brush holders, which are usually of box type. The brushes are made to press on the commutator surface by means of a spring, whose tension can be adjusted with the help of lever. A flexible copper conductor called **pig tail** is used to connect the brush to the external circuit. To avoid wear and tear of commutator, the brushes are made up of soft material like carbon.

1.7.7 Bearings

Ball-bearings are usually used as they are more reliable. For heavy duty machines, roller bearings are preferred.

1.8 Types of Armature Winding

We have seen that there are number of armature conductors, which are connected in specific manner as per the requirement, which is called **armature winding.** According to the way of connecting the conductors, armature winding has basically two types namely,

a) Lap winding b) Wave winding

1.8.1 Lap Winding

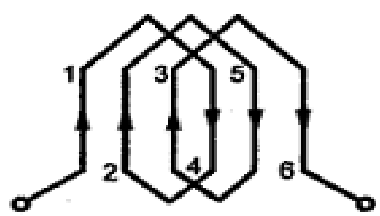


Fig. 1.18 Lap winding

In this case, if connection is started from conductor in slot 1 then connections overlap each other as winding proceeds, till starting point is reached again.

Developed view of part of the armature winding in lap fashion is shown in the Fig. 1.18.

As seen from the Fig. 1.18, there is overlapping of coils while proceeding.

Key Point : *Due to such connection, the **total number of conductors get divided into 'P' number of parallel paths, where P = number of poles in the machine.***

Large number of parallel paths indicate high current capacity of machine hence lap winding is preferred for high current rating generators.

1.8.2 Wave Winding

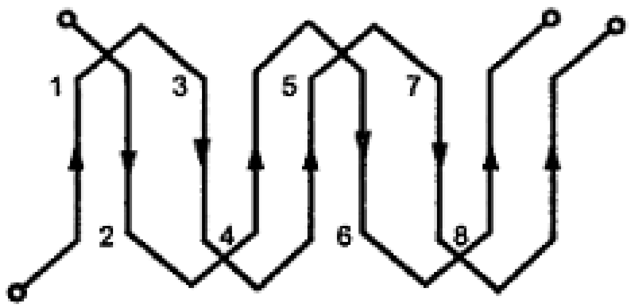


Fig. 1.19 Wave winding

In this type of connection, winding always travels ahead avoiding overlapping. It travels like a progressive wave hence called wave winding. To get an idea of wave winding a part of armature winding in wave fashion is shown in the Fig. 1.19.

Both coils starting from slot 1 and slot 2 are progressing in wave fashion.

Key Point : *Due to this type of connection, the* ***total number of conductors get divided into two number of parallel paths always, irrespective of number of poles of the machine.*** *As number of parallel paths are less, it is preferrable for low current, high voltage capacity generators.*

The number of parallel paths in which armature conductors are divided due to lap or wave fashion of connection is denoted as A. So **A = P** for **lap** connection and **A = 2** for wave connection.

1.8.3 Comparison of Lap and Wave Type Winding

Sr. No	Lap winding	Wave winding
1.	Number of parallel paths (A) = poles (P)	Number of parallel paths (A) = 2 (always)
2.	Number of brush sets required is equal to number of poles.	Number of brush sets required is always equal to two.
3.	Preferable for high current, low voltage capacity generators.	Preferable for high voltage, low current capacity generators.
4.	Normally used for generators of capacity more than 500 A.	Preferred for generators of capacity less than 500 A.

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

Let
P = Number of poles of the generator

ϕ = Flux produced by each pole in webers (Wb)

N = Speed of armature in r.p.m.

Z = Total number of armature conductors

A = Number of parallel paths in which the 'Z' number of conductors are divided

So $\quad A = P \quad$ for lap type of winding

$\quad A = 2 \quad$ for wave type of winding

Now e.m.f. gets induced in the conductor according to Faraday's law of electromagnetic induction. Hence average value of e.m.f. induced in each armature conductor is,

$$e = \text{Rate of cutting the flux} = \frac{d\phi}{dt}$$

Now consider one revolution of conductor. In one revolution, conductor will cut total flux produced by all the poles i.e. $\phi \times P$. While time required to complete one revolution is $\frac{60}{N}$ seconds as speed is N r.p.m.

$$\therefore \quad e = \frac{\phi P}{\frac{60}{N}} = \phi P \frac{N}{60}$$

This is the e.m.f. induced in one conductor. Now the conductors in one parallel path are always in series. There are total Z conductors with A parallel paths, hence $\frac{Z}{A}$ number of conductors are always in series and e.m.f. remains same across all the parallel paths.

$\therefore$ Total e.m.f. can be expressed as,

$$E = \phi P \frac{N}{60} \times \frac{Z}{A} \quad \text{volts}$$

This is nothing but the e.m.f. equation of a d.c. generator.

So
$$\boxed{E = \frac{\phi PNZ}{60\,A} \quad \text{e.m.f. equation}}$$

$$E = \frac{\phi NZ}{60} \quad \text{for lap type as } A = P$$

$$E = \frac{\phi PNZ}{120} \quad \text{for wave type as } A = 2$$

Example 1.1 : *A 4 pole, lap wound, d.c. generator has a useful flux of 0.07 Wb per pole. Calculate the generated e.m.f. when it is rotated at a speed of 900 r.p.m. with the help of prime mover. Armature consists of 440 number of conductors. Also calculate the generated e.m.f. if lap wound armature is replaced by wave wound armature.*

Solution : $P = 4 \quad Z = 440 \quad \phi = 0.07$ Wb and $N = 900$ r.p.m.

$$E = \frac{\phi PNZ}{60A}$$

i) For lap wound, $\quad A = P = 4$

$$\therefore \quad E = \frac{\phi NZ}{60} = \frac{0.07 \times 900 \times 440}{60} = 462 \text{ V}$$

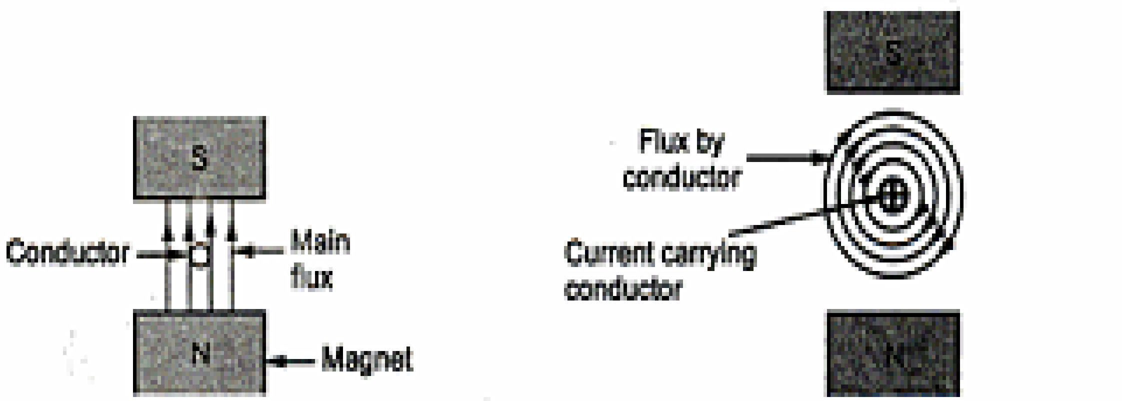
2.1 Introduction

In the last chapter we have discussed about the generators. Now let us see in detail, the various aspects of d.c. motors. A motor is a device which converts an electrical energy into the mechanical energy. The energy conversion process is exactly opposite to that involved in a d.c. generator. In a generator the input mechanical energy is supplied by a prime mover while in a d.c. motor, input electrical energy is supplied by a d.c. supply. The construction of a d.c. machine is same whether it is a motor or a generator, as discussed in the last chapter.

2.2 Principle of Operation of a D.C. Motor

The principle of operation of a d.c. motor can be stated in a single statement as 'when a current carrying conductor is placed in a magnetic field; it experiences a mechanical force'. In a practical d.c. motor, field winding produces a required magnetic field while armature conductors play a role of a current carrying conductors and hence armature conductors experience a force. As conductors are placed in the slots which are on the periphery, the individual force experienced by the conductors acts as a twisting or turning force on the armature which is called a torque. The torque is the product of force and the radius at which this force acts. So overall armature experiences a torque and starts rotating. Let us study this motoring action in detail.

Consider a single conductor placed in a magnetic field as shown in the Fig. 2.1 (a). The magnetic field is produced by a permanent magnet but in a practical d.c. motor it is produced by the field winding when it carries a current.



(a) Conductor in a magnetic field (b) Flux produced by current carrying conductor

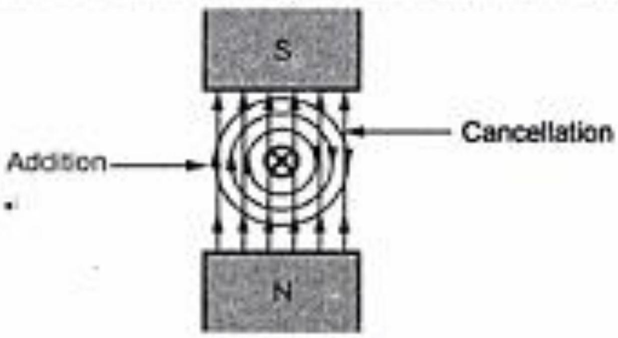
Fig. 2.1

Now this conductor is excited by a separate supply so that it carries a current in a particular direction. Consider that it carries a current away from an observer as shown in the Fig. 2.1 (b). Any current carrying conductor produces its own magnetic field around it, hence this conductor also produces its own flux, around. The direction of this flux can be determined by right hand thumb rule. For direction of current considered, the direction of flux around a conductor is clockwise. For simplicity of understanding, the main flux produced by the permanent magnet is not shown in the Fig. 2.1 (b).

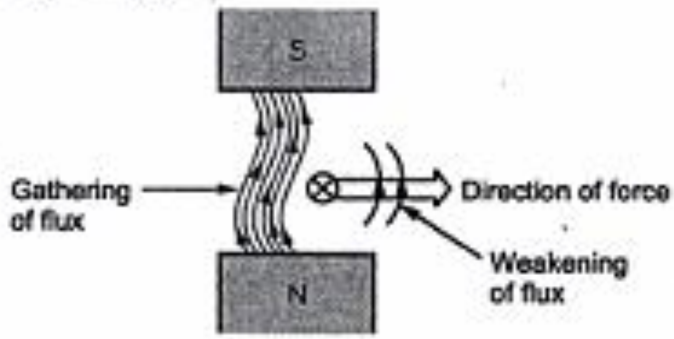
Now there are two fluxes present,

1. The flux produced by the permanent magnet called main flux.
2. The flux produced by the current carrying conductor.

These are shown in the Fig. 2.2 (a). From this, it is clear that on one side of the conductor, both the fluxes are in the same direction. In this case, on the left of the conductor there is gathering of the flux lines as two fluxes help each other. As against this, on the right of the conductor, the two fluxes are in opposite direction and hence try to cancel each other. Due to this, the density of the flux lines in this area gets weakened. So on the left, there exists high flux density area while on the right of the conductor there exists low flux density area as shown in the Fig. 2.2 (b).



(a) Interaction of two fluxes



(b) Force experienced by the conductor

Fig. 2.2

This flux distribution around the conductor acts like a stretched rubber band under tension. This exerts a mechanical force on the conductor which acts from high flux density area towards low flux density area, i.e. from left to right for the case considered as shown in the Fig. 2.2 (b).

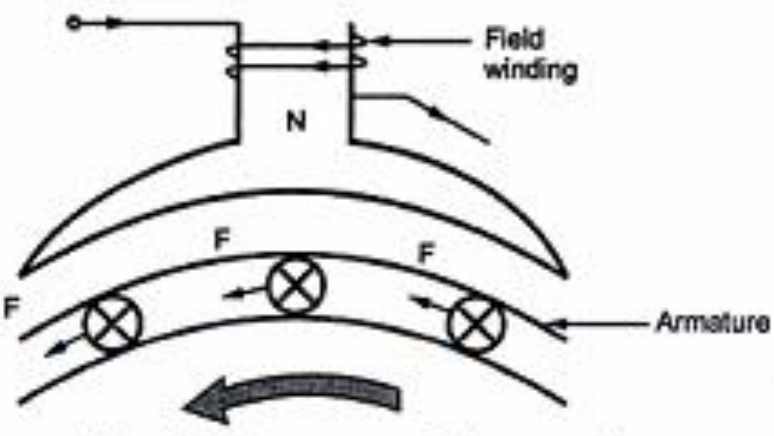


Fig. 2.3 Torque exerted on armature

Key Point : *In the practical d.c. motor, the permanent magnet is replaced by a field winding which produces the required flux called main flux and all the armature conductors, mounted on the periphery of the armature drum, get subjected to the mechanical force. Due to this, overall armature experiences a twisting force called torque and armature of the motor starts rotating.*

2.3 Direction of Rotation of Motor

The magnitude of the force experienced by the conductor in a motor is given by,

$$\boxed{F = B\,l\,I \quad \text{Newtons (N)}}$$

B = Flux density due to the flux produced by the field winding.

l = Active length of the conductor.

I = Magnitude of the current passing through the conductor.

The direction of such force i.e. the direction of rotation of a motor can be determined by Fleming's left hand rule. So **Fleming's right hand rule** is to determine direction of induced e.m.f. i.e. for **generating action** while **Fleming's left hand rule** is to determine direction of force experienced i.e. for **motoring action.**

2.3.1 Fleming's Left Hand Rule

The rule states that, 'Outstretch the three fingers of the left hand namely the first finger, middle finger and thumb such that they are mutually perpendicular to each other. Now point the first finger in the direction of magnetic field and the middle finger in the direction of the current then the thumb gives the direction of the force experienced by the conductor'.

The Fleming's left hand rule can be diagramatically shown as in the Fig. 2.4.

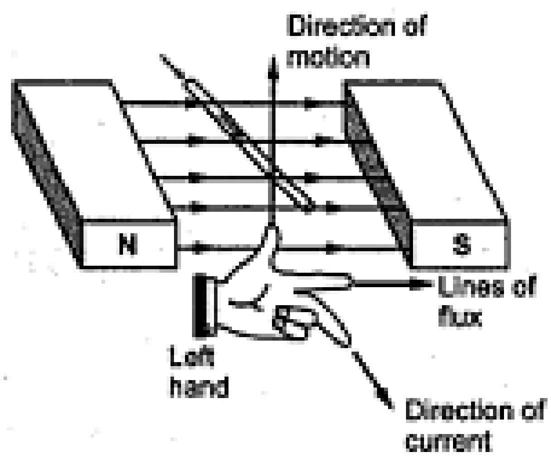


Fig. 2.4 Fleming's left hand rule

Apply the rule to crosscheck the direction of force experienced by a single conductor, placed in the magnetic field, shown in the Fig. 2.5 (a), (b), (c) and (d).

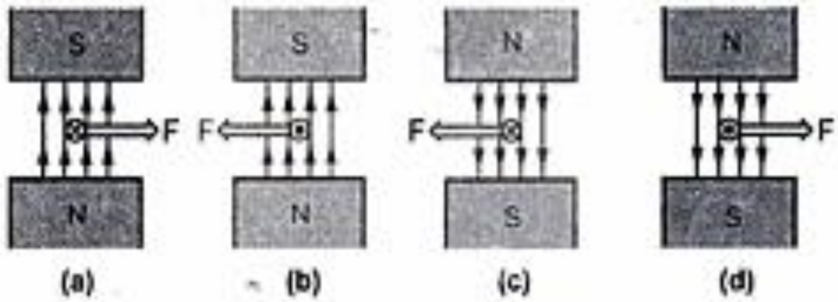


Fig. 2.5 Direction of force experienced by conductor

It can be seen from the Fig. 2.5 that if the direction of the main field in which current carrying conductor is placed, is reversed, force experienced by the conductor reverses its direction. Similarly keeping main flux direction unchanged, the direction of current passing through the conductor is reversed, the force experienced by the conductor reverses its direction. However if both the directions are reversed, the direction of the force experienced remains the same.

> **Key Point** : *So in a practical motor, to reverse its direction of rotation, either direction of main field produced by the field winding is reversed or direction of the current passing through the armature is reversed.*

The direction of the main field can be reversed by changing the direction of current passing through the field winding, which is possible by interchanging the polarities of supply which is given to the field winding. In short, to have a motoring action two fluxes must exist, the interaction of which produces a torque.

2.4 Significance of Back E.M.F.

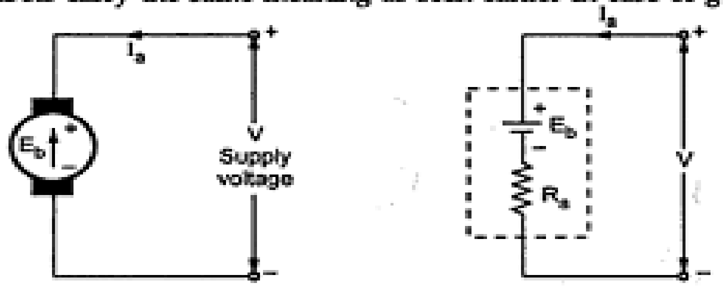
It is seen in the generating action, that when a conductor cuts the lines of flux, e.m.f. gets induced in the conductor. The question is obvious that in a d.c. motor, after a motoring action, armature starts rotating and armature conductors cut the main flux. So is there a generating action existing in a motor ? The answer to this question is 'Yes'.

After a motoring action, there exists a generating action. There is an induced e.m.f. in the rotating armature conductors according to Faraday's law of electromagnetic induction. This induced e.m.f. in the armature always acts in the opposite direction of the supply voltage. This is according to the **Lenz's law** which states that the direction of the induced e.m.f. is always so as to oppose the cause producing it. In a d.c. motor, electrical input i.e. the supply voltage is the cause and hence this induced e.m.f. opposes the supply voltage. This e.m.f. tries to set up a current through the armature which is in the opposite direction to that, which supply voltage is forcing through the conductor.

So as this e.m.f. always opposes the supply voltage, it is called **back e.m.f.** and denoted as E_b. Though it is denoted as E_b, basically it gets generated by the generating action which we have seen earlier in case of generators. So its magnitude can be determined by the e.m.f. equation which is derived earlier. So,

$$\boxed{E_b = \frac{\phi P N Z}{60\,A} \text{ volts}}$$

where all symbols carry the same meaning as seen earlier in case of generators.



(a) Back e.m.f. in a d.c. motor **Fig. 2.6** (b) Equivalent circuit

This e.m.f. is shown schematically in the Fig. 2.6 (a). So if V is supply voltage in volts and R_a is the value of the armature resistance, the equivalent electric circuit can be shown as in the Fig. 2.6 (b).

2.4.1 Voltage Equation of a D.C. Motor

In case of a generator, generated e.m.f. has to supply armature resistance drop and remaining part is available across the load as a terminal voltage. But in case of d.c. motor, supply voltage V has to overcome back e.m.f. E_b which is opposing V and also various drops as armature resistance drop $I_a R_a$, brush drop etc. Infact the electrical work done in overcoming the back e.m.f. gets converted into the mechanical energy developed in the armature. Hence the voltage equation of a d.c. motor can be written as,

$$\boxed{V = E_b + I_a R_a + \text{brush drop}}$$

Neglecting the brush drop, the generalised voltage equation is,

$$V = E_b + I_a R_a$$

The back e.m.f. is always less than supply voltage ($E_b < V$). But R_a is very small hence under normal running conditions, the difference between back e.m.f. and supply voltage is very small. The net voltage across the armature is the difference between the supply voltage and back e.m.f. which decides the armature current. Hence from the voltage equation we can write,

$$\boxed{I_a = \frac{V - E_b}{R_a}}$$

Key Point : *Voltage equation gets changed a little bit depending upon the type of the motor, which is discussed later.*

2.4.2 Back E.M.F. as a Regulating Mechanism

Due to the presence of back e.m.f. the d.c. motor becomes a regulating machine i.e. motor adjusts itself to draw the armature current just enough to satisfy the load demand. The basic principle of this fact is that the back e.m.f. is proportional to speed, $E_b \propto N$.

When load is suddenly put on to the motor, motor tries to slow down. So speed of the motor reduces due to which back e.m.f. also decreases. So the net voltage across the armature $(V - E_b)$ increases and motor draws more armature current. As $F = B\, l\, I$, due to increased current, force experienced by the conductors and hence the torque on the armature increases. The increase in the torque is just sufficient to satisfy increased load demand. The motor speed stops decreasing when the armature current is just enough to produce torque demanded by the new load.

When load on the motor is decreased, the speed of the motor tries to increase. Hence back e.m.f. increases. This causes $(V - E_b)$ to reduce which eventually reduces the current drawn by the armature. The motor speed stops increasing when the armature current is just enough to produce the less torque required by the new load.

Key Point : *So back e.m.f. regulates the flow of armature current and it automatically alters the armature current to meet the load requirement. This is the practical significance of the back e.m.f.*

2.6 Torque Equation of a D.C. Motor

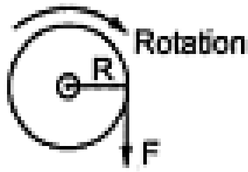


Fig. 2.7

It is seen that the turning or twisting force about an axis is called torque. Consider a wheel of radius R meters acted upon by a circumferential force F newtons as shown in the Fig. 2.7.

The wheel is rotating at a speed of N r.p.m.

Then angular speed of the wheel is,

$$\omega = \frac{2\pi N}{60} \quad \text{rad/sec}$$

So workdone in one revolution is,

$$W = F \times \text{distance travelled in one revolution}$$

$$= F \times 2\pi R \quad \text{joules}$$

And $$P = \text{Power developed} = \frac{\text{Workdone}}{\text{Time}}$$

$$= \frac{F \times 2\pi R}{\text{Time for 1 rev}} = \frac{F \times 2\pi R}{\left(\frac{60}{N}\right)} = (F \times R) \times \left(\frac{2\pi N}{60}\right)$$

$\therefore$ $$P = T \times \omega \quad \text{watts}$$

Where T = Torque in N - m

ω = Angular speed in rad/sec.

Let T_a be the gross torque developed by the armature of the motor. It is also called armature torque. The gross mechanical power developed in the armature is $E_b I_a$, as seen from the power equation. So if speed of the motor is N r.p.m. then,

Power in armature = Armature torque $\times \omega$

$\therefore$ $$E_b I_a = T_a \times \frac{2\pi N}{60}$$

but E_b in a motor is given by,

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

$\therefore$ $$\frac{\phi P N Z}{60 A} \times I_a = T_a \times \frac{2\pi N}{60}$$

$\therefore$ $$\boxed{\begin{aligned} T_a &= \frac{1}{2\pi}\phi I_a \times \frac{PZ}{A} \\ T_a &= 0.159\,\phi I_a \cdot \frac{PZ}{A} \quad \text{N-m} \end{aligned}}$$

This is the torque equation of a d.c. motor.

2.12 D.C. Motor Characteristics

The performance of a d.c. motor under various conditions can be judged by the following characteristics.

i) Torque - armature current characteristics (T Vs I_a) :

The graph showing the relationship between the torque and the armature current is called a torque-armature current characteristic. These are also called electrical characteristics.

ii) Speed - armature current characteristics (N Vs I_a) :

The graph showing the relationship between the speed and armature current characteristics.

iii) Speed - torque characteristics (N Vs T) :

The graph showing the relationship between the speed and the torque of the motor is called speed-torque characteristics of the motor. These are also called mechanical characteristics.

The nature of these characteristics can easily be obtained by using speed and torque equations derived in section 2.11. These characteristics play a very important role in selecting a type of motor for a particular application.

2.13 Characteristics of D.C. Shunt Motor

i) Torque - armature current characteristics

For a d.c. motor $T \propto \phi I_a$

For a constant values of R_{sh} and supply voltage V, I_{sh} is also constant and hence flux is also constant.

$$\therefore \qquad \boxed{T_a \propto I_a}$$

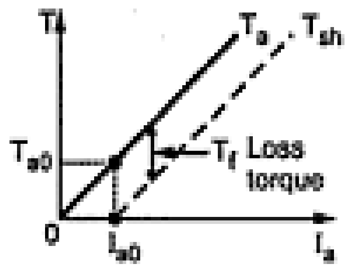


Fig. 2.13 T Vs I_a for shunt motor

The equation represents a straight line, passing through the origin, as shown in the Fig. 2.13. Torque increases linearily with armature current. It is seen earlier that armature current is decided by the load. So as load increases, armature current increases, increasing the torque developed linearly.

Now if shaft torque is plotted against armature current, it is known that shaft torque is less than the armature torque and the difference between the two is loss torque T_f as shown. On no load $T_{sh} = 0$ but armature torque is present which is just enough to overcome stray losses shown as T_{a0}. The current required is I_{a0} on no load to produce T_{a0} and hence T_{sh} graph has an intercept of I_{a0} on the current axis.

To generate high starting torque, this type of motor requires a large value of armature current at start. This may damage the motor hence d.c. shunt motors can develop moderate starting torque and hence suitable for such applications where starting torque requirement is moderate.

ii) Speed - armature current characteristics

From the speed equation we get,

$$N \propto \frac{V - I_a R_a}{\phi}$$

$$\propto V - I_a R_a \qquad \text{as } \phi \text{ is constant.}$$

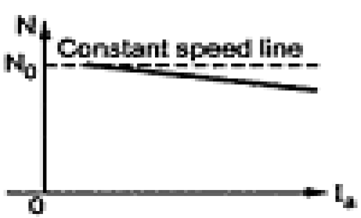


Fig. 2.14 N Vs I_a for shunt motor

So as load increases, the armature current increases and hence drop $I_a R_a$ also increases.

Hence for constant supply voltage, $V - I_a R_a$ decreases and hence speed reduces. But as R_a is very small, for change in I_a from no load to full load, drop $I_a R_a$ is very small and hence drop in speed is also not significant from no load to full load.

So the characteristics is slightly droping as shown in the Fig. 2.14.

But for all practical purposes these type of motors are considered to be a constant speed motors.

iii) Speed - torque characteristics

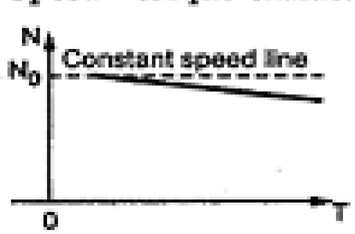


Fig. 2.15 N Vs T for shunt motor

These characteristics can be derived from the above two characteristics. This graph is similar to speed-armature current characteristics as torque is proportional to the armature current. This curve shows that the speed almost remains constant though torque changes from no load to full load conditions. This is shown in the Fig. 2.15.

2.14 Characteristics of D.C. Series Motor

i) Torque - armature current characteristics

In case of series motor the series field winding is carrying the entire armature current. So flux produced is proportional to the armature current.

$$\therefore \qquad \phi \propto I_a$$

Hence $\boxed{T_a \propto \phi I_a \propto I_a^2}$

Thus torque in case of series motor is proportional to the square of the armature current. This relation is parabolic in nature as shown in the Fig. 2.16.

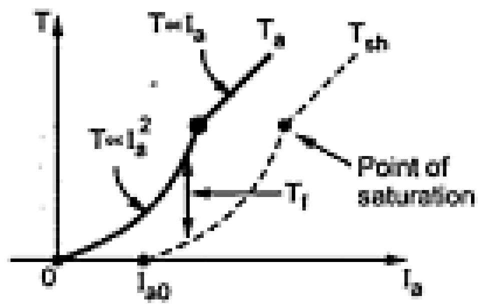


Fig. 2.16 T Vs I_a for series motor

Fig. 2.17 N Vs I_a for series motor

As load increases, armature current increases and torque produced increases proportional to the square of the armature current upto a certain limit.

As the entire I_a passes through the series field, there is a property of an electromagnet called saturation, may occur. Saturation means though the current through the winding increases, the flux produced remains constant. Hence after saturation the characteristics take the shape of straight line as flux becomes constant, as shown. The difference between T_a and T_{sh} is loss torque T_f which is also shown in the Fig. 2.16.

At start as $T \propto I_a^2$, these types of motors can produce high torque for small amount of armature current hence the series motors are suitable for the applications which demand high starting torque.

ii) Speed - armature current characteristics

From the speed equation we get,

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

$$\propto \frac{V - I_a R_a - I_a R_{se}}{I_a} \qquad \text{as } \phi \propto I_a \text{ in case of series motor}$$

Now the values of R_a and R_{se} are so small that the effect of change in I_a on speed overrides the effect of change in $V - I_a R_a - I_a R_{se}$ on the speed.

Hence in the speed equation, $E_b \cong V$ and can be assumed constant. So speed equation reduces to,

$$\boxed{N \propto \frac{1}{I_a}}$$

So speed-armature current characteristics is rectangular hyperbola type as shown in the Fig. 2.17.

iii) Speed - torque characteristics

In case of series motors, $T \propto I_a^2$ and $N \propto \frac{1}{I_a}$

Hence we can write, $\boxed{N \propto \frac{1}{\sqrt{T}}}$

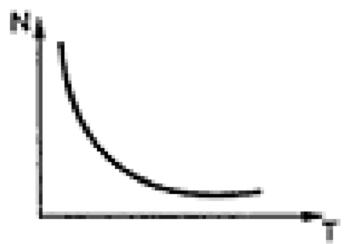


Fig. 2.18 N Vs T for series motor

Thus as torque increases when load increases, the speed decreases. On no load, torque is very less and hence speed increases to dangerously high value. Thus the nature of the speed-torque characteristics is similar to the nature of the speed-armature current characteristics.

The speed-torque characteristics of a series motor is shown in the Fig. 2.18.

2.15 Why Series Motor is Never Started on No Load ?

It is seen earlier that motor armature current is decided by the load. On light load or no load, the armature current drawn by the motor is very small.

In case of a d.c. series motor, $\phi \propto I_a$ and

on no load as I_a is small hence flux produced is also very small.

According to speed equation,

$$N \propto \frac{1}{\phi} \qquad \text{as } E_b \text{ is almost constant.}$$

So on very light load or no load as flux is very small, the motor tries to run at dangerously high speed which may damage the motor mechanically. This can be seen from the speed-armature current and the speed-torque characteristics that on low armature current and low torque condition motor shows a tendency to rotate with dangerously high speed.

This is the reason why series motor should never be started on light loads or no load conditions. For this reason it is not selected for belt drives as breaking or slipping of belt causes to throw the entire load off on the motor and made to run motor with no load which is dangerous.

2.16 Characteristics of D.C. Compound Motor

Compound motor characteristics basically depends on the fact whether the motor is cumulatively compound or differential compound. All the characteristics of the compound motor are the combination of the shunt and series characteristic.

Cumulative compound motor is capable of developing large amount of torque at low speeds just like series motor. However it is not having a disadvantage of series motor even at light or no load. The shunt field winding produces the definite flux and series flux helps the shunt field flux to increase the total flux level.

So cumulative compound motor can run at a reasonable speed and will not run with dangerously high speed like series motor, on light or no load condition.

In differential compound motor, as two fluxes oppose each other, the resultant flux decreases as load increases, thus the machine runs at a higher speed with increase in the load. This property is dangerous as on full load, the motor may try to run with dangerously high speed. So differential compound motor is generally not used in practice.

The various characteristics of both the types of compound motors cumulative and the differential are shown in the Fig. 2.19 (a), (b) and (c).

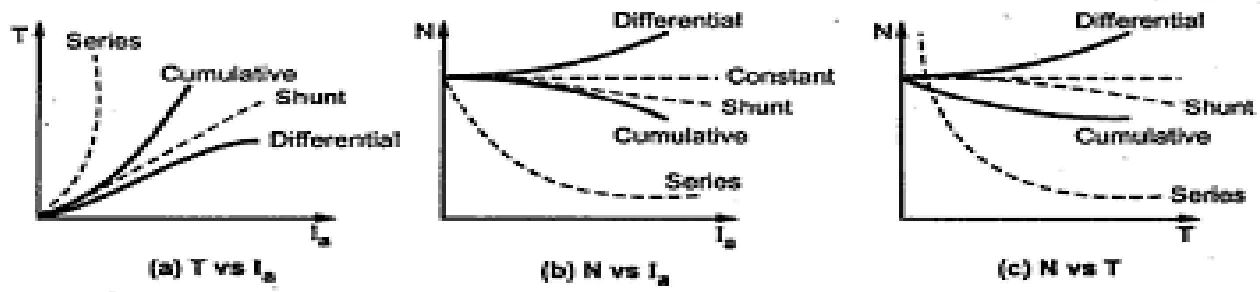


Fig. 2.19 Characteristics of d.c. compound motor

The exact shape of these characteristics depends on the relative contribution of series and shunt field windings. If the shunt field winding is more dominant then the characteristics take the shape of the shunt motor characteristics. While if the series field winding is more dominant then the characteristics take the shape of the series characteristics.

Synchronous Generator

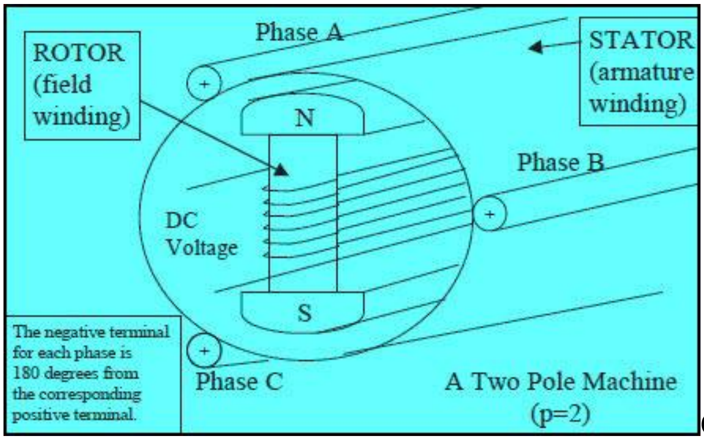
The electrical machine can be defined as a device that converts electrical energy into mechanical energy or mechanical energy into electrical energy. An electrical generator can be defined as an electrical machine that converts mechanical energy into electrical energy. An electrical generator typically consists of two parts; stator and rotor. There are various types of electrical generators such as direct current generators, alternating current generators, vehicular generators, human powered electrical generators, and so on. In this article, let us discuss about synchronous generator working principle.

Synchronous Generator

The rotating and stationary parts of an electrical machine can be called as rotor and stator respectively. The rotor or stator of electrical machines acts as a power-producing component and is called as an armature. The electromagnets or permanent magnets mounted on the stator or rotor are used to provide magnetic field of an electrical machine. The generator in which permanent magnet is used instead of coil to provide excitation field is termed as permanent magnet synchronous generator or also simply called as synchronous generator.

Construction of Synchronous Generator

In general, synchronous generator consists of two parts rotor and stator. The rotor part consists of field poles and stator part consists of armature conductors. The rotation of field poles in the presence of armature conductors induces an alternating voltage which results in electrical power generation.



Construction of Synchronous Generator

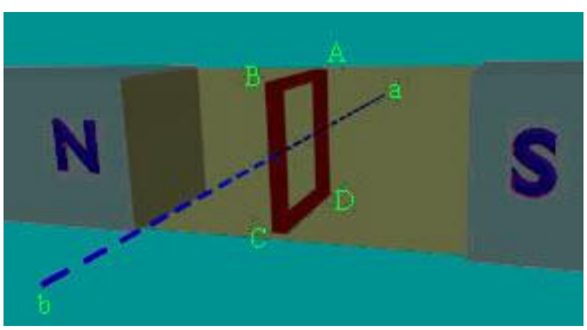
The speed of field poles is synchronous speed and is given by

$$N_s = \frac{120f}{P}$$

Where, ‘f’ indicates alternating current frequency and ‘P’ indicates number of poles.

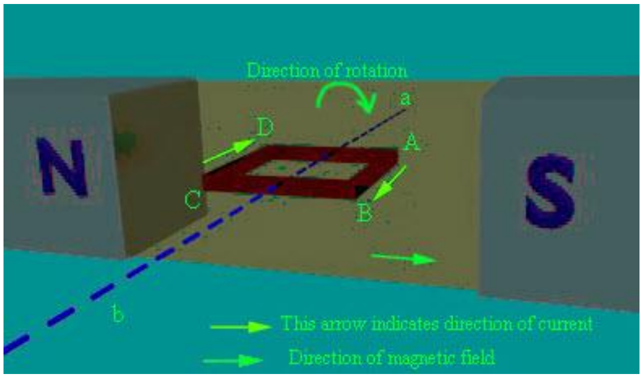
Synchronous Generator Working Principle

The principle of operation of synchronous generator is electromagnetic induction. If there exists a relative motion between the flux and conductors, then an EMF is induced in the conductors. To understand the synchronous generator working principle, let us consider two opposite magnetic poles in between them a rectangular coil or turn is placed as shown in the below figure.



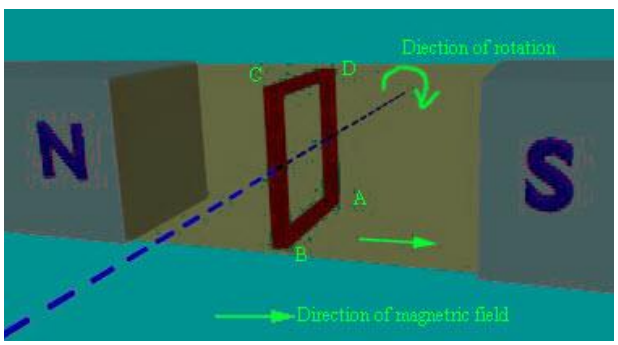
Rectangular Conductor placed in between two opposite Magnetic Poles

If the rectangular turn rotates in clockwise direction against axis a-b as shown in the below figure, then after completing 90 degrees rotation the conductor sides AB and CD comes in front of the S-pole and N-pole respectively. Thus, now we can say that the conductor tangential motion is perpendicular to magnetic flux lines from north to South Pole.



Direction of Rotation of Conductor perpendicular to Magnetic Flux

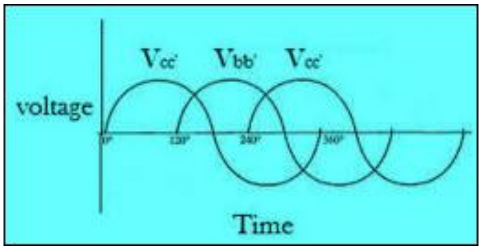
So, here rate of flux cutting by the conductor is maximum and induces current in the conductor, the direction of the induced current can be determined using Fleming's right hand rule. Thus, we can say that current will pass from A to B and from C to D. If the conductor is rotated in a clockwise direction for another 90 degrees, then it will come to a vertical position as shown in the below figure.



Direction of Rotation of Conductor parallel to Magnetic Flux

Now, the position of conductor and magnetic flux lines are parallel to each other and thus, no flux is cutting and no current will be induced in the conductor. Then, while the conductor rotates from clockwise for another 90 degrees, then rectangular turn comes to a horizontal position as shown in the below figure. Such that, the conductors AB and CD are under the N-pole and S-pole respectively. By applying Fleming's right hand rule, current induces in conductor AB from point B to A and current induces in a conductor CD from point D to C. So, the direction of current can be indicated as A – D – C – B and direction of current for the previous horizontal position of rectangular turn is A – B – C – D. If the turn is again rotated towards vertical position, then the induced current again reduces to zero. Thus, for one complete revolution of rectangular turn the current in the conductor reaches to maximum & reduces to zero and then in the opposite direction it reaches to maximum & again reaches to zero. Hence, one complete revolution of rectangular turn produces one full sine wave of current induced in the conductor which can be termed as the generation of alternating current by rotating a turn inside a magnetic field.

Now, if we consider a practical synchronous generator, then field magnets rotate between the stationary armature conductors. The synchronous generator rotor and shaft or turbine blades are mechanically coupled to each other and rotates at synchronous speed. Thus, the magnetic flux cutting produces an induced EMF which causes the current flow in armature conductors. Thus, for each winding the current flows in one direction for the first half cycle and current flows in the other direction for the second half cycle with a time lag of 120 degrees (as they displaced by 120 degrees). Hence, the output power of synchronous generator can be shown as below figure.



UNIT-V

ELECTRICAL INSTALLATIONS

MINIATURE CIRCUIT BREAKER (MCB)

A miniature circuit breaker automatically switches off electrical circuit during abnormal condition of the network means in over load condition as well as faulty condition. Nowadays we use an MCB in low voltage electrical network instead of fuse. The fuse may not sense it but the miniature circuit breaker does it in a more reliable way. MCB is much more sensitive to over current than fuse.

Handling a MCB is electrically safer than a fuse. Quick restoration of supply is possible in case of fuse as because fuses must be re-wireable or replaced for restoring the supply. Restoration is easily possible by just switching it ON. Let’s look at the working of the miniature circuit breaker.

Working principle of the miniature circuit breaker

Whenever continuous over current flows through MCB, the bimetallic strip is heated and deflects by bending. This deflection of bimetallic strip releases mechanical latch. As this mechanical latch is attached with operating mechanism, it causes to open the miniature circuit breaker contacts, and the MCB turns off thereby stopping the current to flow in the circuit. To restart the flow of current the MCB must be manually turned ON. This mechanism protects from the faults arising due to over current or over load.

But during short circuit condition, current rises suddenly, causing electromechanical displacement of plunger associated with a tripping coil or solenoid. The plunger strikes the trip lever causing immediate release of latch mechanism consequently open the circuit breaker contacts. This was a simple explanation of miniature circuit breaker working principle.

An MCB is very simple, easy to use and is not generally repaired. It is just easier to replace. The trip unit is the main part, responsible for its proper working. There are two main types of trip mechanism. A bi-metal provides protection against over load current and an electromagnet provides protection against short-circuit current.

MCB operation

If circuit is overloaded for a long time, the bi-metallic strip becomes over heated and deformed. This deformation of bi metallic strip causes, displacement of latch point. The moving contact of the MCB is arranged by means of spring pressure, with this latch point, that a little displacement of latch causes, release of spring and makes the moving contact to move for opening the MCB.

The current coil or trip coil is placed so that during short circuit fault the magneto-motive force (mmf) of the coil causes its plunger to hit the same latch point and make the latch to be displaced. Again, when operating lever of the miniature circuit breaker is operated by hand, that means when MCB goes off position manually, the same latch point is displaced as a result moving contact separated from fixed contact in same manner.

It may be due to deformation of bi-metallic strip, or increased mmf of trip coil or maybe manual operation, the same latch point is displaced and same deformed spring is released, which ultimately responsible for movement of the moving contact. When the moving contact separated from fixed contact, there may be a high chance of arc. This arc then goes up through the arc runner and enters arc splitters and is finally quenched. When we switch it on, we reset the displaced operating latch to its previous on position and the MCB is ready for another switch off or trip operation.

S.F.U (Switched Fuse Unit)

It is Switched Fuse Unit. It has one switch unit and one fuse unit. When we operate the breaker, the contacts will get closed through switch and then the supply will passthrough the fuse unit to the output. Whereas in a Fuse Switch Unit there is no separate switch and fuse unit. There is only the fuse unit which itself acts as a

switch. When we operate it the fuse unit will close the input and output of the breaker.
SFU has been used to trip the circuit, particularly for high capacity tripping.

Earth-leakage circuit breaker (ELCB)

An Earth-leakage circuit breaker (ELCB) is a safety device used in electrical installations with high Earth impedance to prevent shock. It detects small stray voltages on the metal enclosures of electrical equipment, and interrupts the circuit if a dangerous voltage is detected. Once widely used, more recent installations instead use residual current circuit breakers which instead detect leakage current directly.

Molded Case Circuit Breaker (MCCB)

Definition and Function

A *molded case circuit breaker*, abbreviated MCCB, is a type of electrical protection device that can be used for a wide range of voltages, and frequencies of both 50 Hz and 60 Hz. The main distinctions between molded-case and miniature circuit breaker are that the MCCB can have current ratings of up to 2,500 amperes, and its trip settings are normally adjustable. An additional difference is that MCCBs tend to be much larger than MCBs. As with most types of circuit breakers, an MCCB has three main functions:

Protection against overload – currents above the rated value that last longer than what is normal for the application.

Protection against electrical faults – During a fault such as a short circuit or line fault, there are extremely high currents that must be interrupted immediately.

Switching a circuit on and off – This is a less common function of circuit breakers, but they can be used for that purpose if there isn't an adequate manual switch.

The wide range of current ratings available from molded-case circuit breakers allows them to be used in a wide variety of applications. MCCBs are available with current ratings that range from low values such as 15 amperes, to industrial ratings such as 2,500 amperes. This allows them to be used in both low-power and high-power applications.

Molded Case Circuit Breaker Operating Mechanism

Overload protection is accomplished by means of a thermal mechanism. MCCBs have a bimetallic contact what expands and contracts in response to changes in temperature. Under normal operating conditions, the contact allows electric current through the MCCB. However, as soon as the current exceeds the adjusted trip value, the contact will start to heat and expand until the circuit is interrupted. The thermal protection against overload is designed with a time delay to allow short duration overcurrent, which is a normal part of operation for many devices. However, any overcurrent conditions that last more than what is normally expected represent an overload, and the MCCB is tripped to protect the equipment and personnel.

On the other hand, fault protection is accomplished with electromagnetic induction, and the response is instant. Fault currents should be interrupted immediately, no matter if their duration is short or long. Whenever a fault occurs, the extremely high current induces a magnetic field in a solenoid coil located inside the breaker – this magnetic induction trips a contact and current is interrupted. As a complement to the magnetic protection mechanism, MCCBs have internal arc dissipation measures to facilitate interruption.

Types of Batteries

1) Primary Batteries:

As the name indicates these batteries are meant for single usage. Once these batteries are used they cannot be recharged as the devices are not easily reversible and active materials may not return to their original forms. Battery manufacturers recommend against recharge of primary cells.

Some of the examples for the disposable batteries are the normal AA, AAA batteries which we use in wall clocks, television remote etc. Other name for these batteries is disposable batteries.

Types Battery

2) Secondary Batteries:

Secondary batteries are also called as rechargeable batteries. These batteries can be used and recharges simultaneously. They are usually assembled with active materials with active in the discharged state. Rechargeable batteries are recharged by applying electric current, which reverses the chemical reactions that occur during discharge. Chargers are devices which supply the required current.

Some examples for these rechargeable batteries are the batteries used in mobile phones, MP3 players etc. Devices such as hearing aids and wristwatches use miniature cells and in places such as telephone exchanges or computer data centre's larger batteries are used.

Secondary Batteries

Types of Secondary (rechargeable) Batteries:

1) SMF,

2) Lead Acid,

3) Li

4) NiCad

SMF Battery:

SMF is a sealed maintenance free battery, designed to offer reliable, consistent and low maintenance power for UPS applications. These batteries can be subject to deep cycle applications and minimum maintenance in rural and power deficit areas. These batteries are available from 12V.

In today’s informative world, one can’t overlook the requirement for battery systems are designed to recover crucial qualified data and information and run basic instrumentations for desired durations. Batteries are required to deliver instant power. Unreliable and inferior batteries can result in the loss of data and equipment shutdowns that can cost companies considerable financial losses. Subsequently, the UPS segments calls for the utilization of a reliable and proven battery system.

SMF Battery

Lithium (Li) Battery:

We all use it in portable devices such as cell phone, a laptop computer or a power tool. The lithium battery has been one of the greatest achievements in portable power in the last decade; with use of lithium batteries we have been able to shift from black and white mobile to color mobiles with additional features like GPS, email alerts etc. These are the high energy density potential devices for higher capacities. And relatively low self-discharge batteries. Also Special cells can provide very high current to applications such as power tools.

Li Battery

Nickel Cadmium (Nicd) Battery:

The Nickel Cadmium batteries have the advantage of being recharged many times and possess a relatively constant potential during discharge and have more electrical and physical withstanding capacity. This battery uses nickel oxide for cathode, a cadmium compound for anode and potassium hydroxide solution as its electrolyte.

Characteristics ofa Battery

There are many characteristics that can help to identify a battery and we can distinguish the three main ones as: chemistry, voltage and specific energy (capacity). However, if the **battery** is only a starter, it also delivers cold cranking amps (CCA), which permits to offer high current at cold temperatures.

In the following paragraphs are listed the primary **characteristics of a battery**, along with the corresponding descriptions.

CHEMISTRY

The main **battery chemistries** are lead, nickel and lithium. They all need a specific designated charger, this is why charging these batteries on a different charger from their own might cause an incorrect charge, despite it may seem to work at first.

This happens because of the different regulatory requirement of each chemistry.

VOLTAGE

A battery features a **nominal voltage**. Along with the amount of cells connected in series, chemistry provides the open circuit voltage (OCV), which is about 5-7% higher on a fully charged battery.

It is important to check the correct **nominal voltage of a battery** before connecting it.

CAPACITY

The **capacity of a battery** indicates the specific energy in ampere-hours (Ah), which represents the discharge current that a battery is able to issue over the course of time.

Installing a battery that has a higher Ah than indicated offers a longer runtime, just as a smaller Ah provides a shorter runtime. Moreover, charging a larger battery will take more time than charging a smaller one, but the Ah divergence must not surpass 25%.

COLD CRANKING AMPS (CCA)

Every **starter battery** is marked with cold cranking amps, also abbreviated CCA. The number denotes the amount of **amps** that the battery is able to provide at -18°C.

SPECIFIC ENERGY AND ENERGY DENSITY

Specific energy expresses the **capacity of a battery** in weight (Wh/kg), and it can also be called gravimetric **energy density**. Energy density, also called volumetric energy density, describes volume in liters (Wh/l).

Those products that need a long runtime at moderate load are optimized for high specific energy.

SPECIFIC POWER

Loading capability is designated by **specific power**, also called gravimetric power density. Power tools need a battery made for high specific power that features a lowered specific energy (capacity).

C-RATES

C-rates indicate how much time a battery takes to charge or discharge. If the battery is at 1C, it charges and discharges at a current that is equal to the marked Ah rating; at 0,5C, the time is doubled and the current is half; at 0,1C the time is 10-fold and the current is one-tenth.

LOAD

Load describes the current drawn from a battery. The voltage drops under load because of the internal battery resistance and the state of charge (SoC), causing the end of discharge.

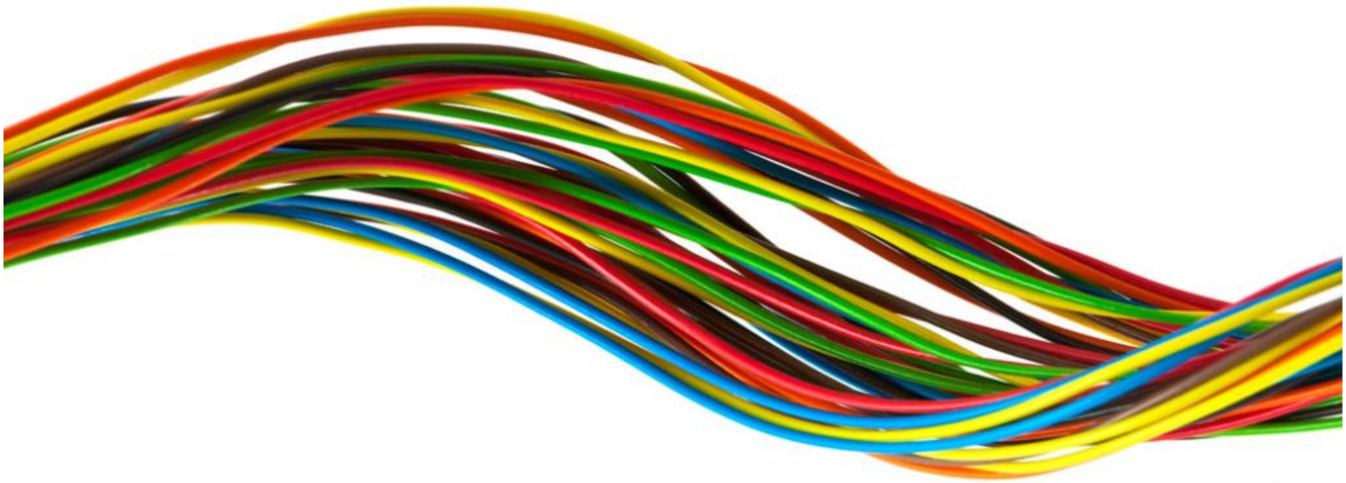
Power is measured in watts (W) and it represents the current provided; energy is the physical work over the course of time and it is indicated in watt-hours (Wh).

WATTS AND VOLT-AMPS (VA)

Watts and Volt-amps (VA) represent, respectively, the real power metered and the apparent power influenced by a reactive load.

Watt and VA readings are equal if measured on a resistive load. A reactive load triggers a phase shift between voltage and current, causing the lowering of the power factor (pf) and the ideal one (1) to 0,7 or less. The dimensioning of electrical wiring and circuit breakers has to be based on VA power.

Electrical Wire



Some factors that will affect your choice of electrical wiring include color, label information and applications. The information printed on the wire covering is all that you need to choose the correct wire for your home. Here's some detailed information on the various features of electrical wire, which will help you choose the correct composition:

1. **Size of Wires** – Each application requires a certain wire size for installation, and the right size for a specific application is determined by the wire gauge. Sizing of wire is done by the American wire gauge system. Common wire sizes are 10, 12 and 14 – a higher number means a smaller wire size, and affects the amount of power it can carry. For example, a low-voltage lamp cord with 10 Amps will require 18-gauge wire, while service panels or subpanels with 100 Amps will require 2-gauge wire..

2**. Wire Lettering** – The letters THHN, THWN, THW and XHHN represent the main insulation types of individual wires. These letters depict the following NEC requirements:.

T – Thermoplastic insulation

H – Heat resistance

HH – High heat resistance (up to 194°F)

W – Suitable for wet locations

N – Nylon coating, resistant to damage by oil or gas

X – Synthetic polymer that is flame-resistant

3**. Types of Wires –** There are mainly 5 types of wire: .

Triplex Wires: Triplex wires are usually used in single-phase service drop conductors, between the power pole and weather heads. They are composed of two insulated aluminum wires wrapped with a third bare wire which is used as a common neutral. The neutral is usually of a smaller gauge and grounded at both the electric meter and the transformer.

Main Feeder Wires: Main power feeder wires are the wires that connect the service weather head to the house. They're made with stranded or solid THHN wire and the cable installed is 25% more than the load required.

Panel Feed Wires: Panel feed cables are generally black insulated THHN wire. These are used to power the main junction box and the circuit breaker panels. Just like main power feeder wires, the cables should be rated for 25% more than the actual load.

Non-Metallic Sheathed Wires: Non-metallic sheath wire, or Romex, is used in most homes and has 2-3 conductors, each with plastic insulation, and a bare ground wire. The individual wires are covered with another layer of non-metallic sheathing. Since it's relatively cheaper and available in ratings for 15, 20 and 20 amps, this type is preferred for in-house wiring.

Single Strand Wires: Single strand wire also uses THHN wire, though there are other variants. Each wire is separate and multiple wires can be drawn together through a pipe easily. Single strand wires are the most popular choice for layouts that use pipes to contain wires.

4. Color Codes – Different color wires serve different purposes, like:

Black: Hot wire, for switches or outlets.

Red: Hot wire, for switch legs. Also for connecting wire between 2 hardwired smoke detectors.

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: Only for grounding.

5. Wire Gauge, Ampacity and Wattage Load – To determine the correct wire, it is important to understand what ampacity and wattage a wire can carry per gauge. Wire gauge is the size of the wire, ampacity is how much electricity can flow through the wire and wattage is the load a wire can take, which is always mentioned on the appliances...

Understanding Electrical Cable

An electrical cable also has different types, color and application as its determining factors. Here's a brief about cables that you need to understand to determine the correct cable for your home.

Types of Electrical Cables – There are more than 20 different types of cables available today, designed for applications ranging from transmission to heavy industrial use.

Some of the most commonly-used ones include

Non-Metallic Sheathed Cable: These cables are also known as non-metallic building wire or NM cables. They feature a flexible plastic jacket with two to four wires (TECK cables are covered with thermoplastic insulation) and a bare wire for grounding. Special varieties of this cable are used for underground or outdoor use, but NM-B and NM-C non-metallic sheathed cables are the most common form of indoor residential cabling.

Underground Feeder Cable: These cables are quite similar to NM cables, but instead of each wire being individually wrapped in thermoplastic, wires are grouped together and embedded in the flexible material. Available in a variety of gauge sizes, UF cables are often used for outdoor lighting and in-ground applications. Their high water-resistance makes them ideal for damp areas like gardens as well as open-to-air lamps, pumps, etc.

Metallic Sheathed Cable: Also known as armored or BX cables, metal-sheathed cables are often used to supply mains electricity or for large appliances. They feature three plain stranded copper wires (one wire for the current, one grounding wire and one neutral wire) that are insulated with cross-linked polyethylene, PVC bedding and a black PVC sheathing. BX cables with steel wire sheathing are often used for outdoor applications and high-stress installations.

Multi-Conductor Cable: This is a cable type that is commonly used in homes, since it is simple to use and well-insulated. Multi-conductor or multi-core (MC) cables feature more than one conductor, each of which is insulated individually. In addition, an outer insulation layer is added for extra security. Different varieties are used in industries, like the audio multicore 'snake cable' used in the music industry.

Coaxial Cable : A coaxial (sometimes helix) cable features a tubular insulating layer that protects an inner conductor which is further surrounded by a tubular conducting shield, and might also feature an outer sheath for extra insulation. Called 'coaxial' since the two inner shields share the same geometric axis, these cables are normally used for carrying television signals and connecting video equipment.

Unshielded Twisted Pair Cable: Like the name suggests, this type consists of two wires that are twisted together. The individual wires are not insulated, which makes this cable perfect for signal transmission and video applications. Since they are more affordable than coaxial or optical fiber cables, UTP cables are often used in telephones, security cameras and data networks. For indoor use, UTP cables with copper wires or solid copper cores are a popular choice, since they are flexible and can be easily bent for in-wall installation.

Ribbon Cable: Ribbon cables are often used in computers and peripherals, with various conducting wires that run parallel to each other on a flat plane, leading to a visual resemblance to flat ribbons. These cables are quite flexible and can only handle low voltage applications.

Direct-Buried Cable: Also known as DBCs, these cables are specially-designed coaxial or bundled fiber-optic cables, which do not require any added sheathing, insulation or piping before being buried underground. They feature a heavy metal core with many layers of banded metal sheathing, heavy rubber coverings, shock-absorbing gel and waterproof wrapped thread-fortified tape. High tolerance to temperature changes, moisture and other environmental factors makes them a popular choice for transmission or communication requirements.

Twin-Lead Cable: These are flat two-wire cables that are used for transmission between an antenna and receiver, like TV and radio.

Twin axialCable: This is a variant of coaxial cables, which features two inner conductors instead of one and is used for very-short-range high-speed signals.

Paired Cable: With two individually insulated conductors, this cable is normally used in DC or low-frequency AC applications.

Twisted Pair: This cable is similar to paired cables, but the inner insulated wires are twisted or intertwined.

2. Cable Color Code – Color coding of cable insulation is done to determine active, neutral and earth conductors. The NEC has not prescribed any color for phase/active conductors. Different countries/regions have different cable color coding, and it is essential to know what is applicable in your region. However, active conductors cannot be green/yellow, green, yellow, light blue or black...

Cable Size – Cable size is the gauge of individual wires within the cable, such as 14, 12, 10 etc. – again, the bigger the number, the smaller the size. The number of wires follows the wire-gauge on a cable. So, 10/3 would indicate the presence of 3 wires of 10-gauge within the cable. Ground wire, if present, is not indicated by this number, and is represented by the letter 'G'.

Safety is very important, and if your installation of wires and cables is not proper, it could lead to accidents. Before you start any electrical project that includes wiring and cabling, you need to obtain permission from your local building inspector. Once the job is done, get the installation inspected for compliance with local codes and regulations.

Electrical Earthing

Definition: The process of transferring the immediate discharge of the electrical energy directly to the earth by the help of the low resistance wire **is known** as the electrical earthing. The electrical earthing is done by connecting the non-current carrying part of the equipment or neutral of supply system to the ground.

Mostly, the galvanized iron is used for the earthing. The **earthing provides the simple path to the leakage current**. The short-circuit current of the equipment passes to the earth which has zero potential. Thus, protects the system and equipment from damage.

Types of Electrical Earthing

The electrical equipment mainly consists of two non-current carrying parts. These parts are neutral of the system or frame of the electrical equipment. From the earthing of these two non-current carrying parts of the electrical system earthing can be classified into two types.

Neutral Earthing

Equipment Earthing.

Neutral Earthing

In neutral earthing, the neutral of the system is directly connected to earth by the help of the GI wire. The neutral earthing is also called the system earthing. Such type of earthing is mostly provided to the system which has star winding. For example, the neutral earthing is provided in the generator, transformer, motor etc.

Equipment Earthing

Such type of earthing is provided to the electrical equipment. The non-current carrying part of the equipment like their metallic frame is connected to the earth by the help of the conducting wire. If any fault occurs in the apparatus, the short-circuit current to pass the earth by the help of wire. Thus, protect the system from damage.

Importance of Earthing

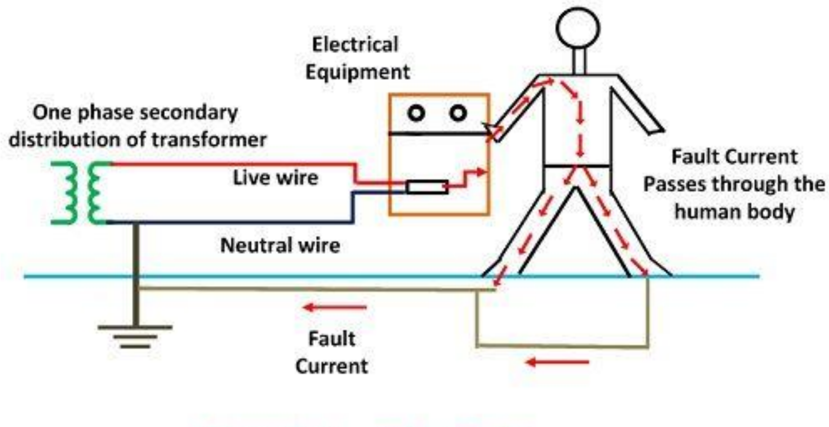
The earthing is essential because of the following reasons

The earthing protects the personnel from the short-circuit current.

The earthing provides the easiest path to the flow of short-circuit current even after the failure of the insulation.

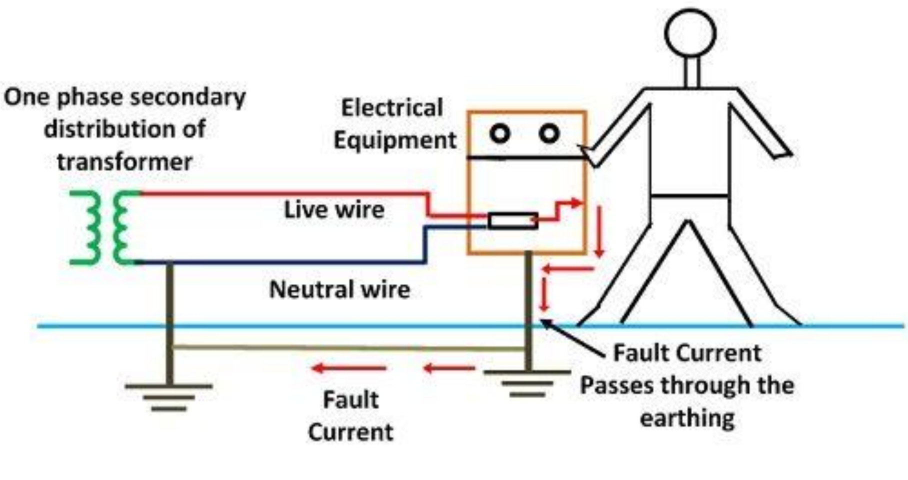
The earthing protects the apparatus and personnel from the high voltage surges and lightning discharge.

Earthing can be done by electrically connecting the respective parts in the installation to some system of electrical conductors or electrodes placed near the soil or below the ground level. The earthing mat or electrode under the ground level have flat iron riser through which all the non-current-carrying metallic parts of the equipment are connected.



Electrical System Without Earthing

When the fault occurs the fault current from the equipment flows through the earthing system to the earth and thereby protect the equipment from the fault current. At the time of the fault, the earth mat conductors rise to the voltage which is equal to the resistance of the earth mat multiplied by a ground fault.



Electrical System With Earthing

The contacting assembly is called earthing. The metallic conductors connecting the parts of the installation with the earthing are called electrical connection. The earthing and the earthing connection together called the earthing system.

<u>How can I calculate the consumption of an electrical appliance?</u>

To calculate the consumption of an electrical appliance in kWh, you have to take into account three factors:

the **capacity** of your electrical appliance, expressed in **watt**.

the **number of hours** that the appliance is in use in one day.

the **number of days** per year when the appliance is in use.

The calculation is as follows:

[number of hours' use] x [number of days' use] x ([capacity of appliance expressed in watt] / 1,000) = number of kWh

The capacity should be divided by 1,000 to convert the number of watts into the number of kilowatts. This finally gives us the number of kWh (kilowatt hours).

Calculation for the energy consumption of a radio alarm

A radio alarm is on all the time and therefore uses energy continuously.

hours / day	24 hours
days / year	365
Capacity of radio alarm	10 watts

Annual energy consumption of radio alarm: 24 x 365 x (10 watts / 1,000) = 87.6 kWh

Calculation for the energy consumption of a vacuum cleaner

In the table below we assume that the vacuum cleaner is used for two hours once a week.

hours / day	2 hours
days / year	52 days

Capacity of vacuum cleaner	2000 watts

Annual energy consumption of vacuum cleaner: 2 x 52 x (2,000 watts / 1,000) = ***208 kWh***

13. <u>Additional/Missing Topics</u>

Power Factor | Calculation and Power Factor Improvement

In general power is the capacity to do work. In electrical domain, electrical power is the amount of electrical energy that can be transferred to some other form (heat, light etc.) per unit time. Mathematically it is the product of voltage drop across the element and current flowing through it. Considering first the DC circuits, having only DC voltage sources, the inductors and capacitors behave as short circuit and open circuit respectively in steady state. Hence the entire circuit behaves as resistive circuit and the entire electrical power is dissipated in the form of heat. Here the voltage and current are in same phase and the total electrical power is given by

Now coming to AC circuit, here both inductor and capacitor offer a certain amount of impedance given by,

The inductor stores electrical energy in the form of magnetic energy and capacitor stores electrical energy in the form of electrostatic energy. Neither of them dissipates it. Further, there is a phase shift between voltage and current. Hence when we consider the entire circuit consisting of resistor, inductor and capacitor, there exists some phase difference between the source voltage and current. The cosine of this phase difference is called electrical power factor. This factor ($-1 < \cos\varphi < 1$) represents the fraction of the total power that is used to do the useful work. The other fraction of electrical power is stored in the form of magnetic energy or electrostatic energy in the inductor and capacitor respectively.

The total power in this case is, This is called apparent power and its unit is VA (Volt Amp) and denoted by 'S'.
A fraction of this total electrical power which does our useful work is called as active power.
We denote it as 'P'.
P = Active power = Total electrical power.$\cos\varphi$ and its unit is watt.

The other fraction of power is called reactive power. Reactive power does no useful work, but it is required for the active work to be done.
We denote it with 'Q' and mathematically is given by,

Q = Reactive power = Total electrical power.$\sin\varphi$ and its unit is VAR (Volt Amp Reactive). This reactive power oscillates between source and load.
To help understand this better all these power are represented in the form of triangle.

Mathematically, S2 = P2 + Q2 and electrical power factor is active power / apparent power.
Power Factor Improvement
The term power factor comes into the picture in AC circuits only. Mathematically it is the cosine of the phase difference between the source voltage and current. It refers to the fraction of total power (apparent power) which is utilized to do the useful work called active power

.

Need for Power Factor Improvement
Real power is given by $P = VI\cos\varphi$. The electrical current is inversely proportional to $\cos\varphi$ for transferring a given amount of power at a certain voltage. Hence higher the pf lower will be the current flowing. A small current flow requires a less cross-sectional area of conductors, and thus it saves conductors and money.
From above relation we see having poor power factor increases the current flowing in a conductor and thus copper loss increases. Further large voltage drop occurs in alternator, electrical transformer and transmission and distribution lines which gives very poor voltage regulation.

Further the KVA rating of machines is also reduced by having higher power factor as, Hence, the size and cost of the machine also reduced. So, electrical power factor should be maintained close to unity.

Methods of Power Factor Improvement

Capacitors: Improving power factor means reducing the phase difference between voltage and current. Since the majority of loads are of inductive nature, they require some amount of reactive power for them to function. The capacitor or bank of capacitors installed parallel to the load provides this reactive power. They act as a source of local reactive power, and thus less reactive power flows through the line. They reduce the phase difference between the voltage and current.

Synchronous Condenser: They are 3 phase synchronous motor with no load attached to its shaft. The synchronous motor has the characteristics of operating under any power factor leading, lagging or unity depending upon the excitation. For inductive loads, a synchronous condenser is connected towards load side and is overexcited. Synchronous condenser makes it behave like a capacitor. It draws the lagging current from the supply or supplies the reactive power.

Phase Advancer: This is an AC exciter mainly used to improve pf of induction motor. They are mounted on the shaft of the motor and connected to the rotor circuit of the motor. It improves the power factor by providing the exciting ampere turns to produce required flux at slip frequency. Further, if ampere-turns increase, it can be made to operate at leading power factor.

Power Factor Calculation

In power factor calculation, we measure the source voltage and current drawn using a voltmeter and ammeter respectively. A wattmeter is used to get the active power.

Now, we know $P = VI\cos\varphi$ watt

Hence, we can get the electrical power factor. Now we can calculate the reactive power $Q = VI\sin\varphi$ VAR This reactive power can now be supplied from the capacitor installed in parallel with load in local. Value of capacitor is calculated as per following formula

: I

IMPORTANT: In power factor improvement, the reactive power requirement by the load does not change. It is just supplied by some device in local, thus reducing the burden on source to provide the required reactive power.

14. UNIVERSITY QUESTION PAPERS OF PREVIOUS YEARS

AR18

Course Code: 18EE1201

Geethanjali College of Engineering and Technology (Autonomous), Hyderabad

I B.Tech (CSE/ECE) II Semester (Regular) Examinations, May 2019

Basic Electrical Engineering

Time: 3 hours | Max. Marks: 70

Answer All Questions

PART-A — 10 X 2M = 20M

1 a. Give the statement of Thevenin's theorem.

b. The voltage across 5Ω resistor is 10 volts, find the current and power dissipated in that resistor.

c. Define alternating quantity.

d. Define form factor and peak factor.

e. Discuss the properties of ideal transformer.

f. Discuss the significance of j-operator in analysis of AC circuits.

g. What is meant by Bandwidth and Q factor?

h. Write expression for resonant frequency and explain terms involved.

i. Define slip and synchronous speed.

j. Classify earth leakage circuit breaker.

PART-B — 5 X 10M = 50M

2 a. Calculate V_o and I_o in the circuit shown in figure 1. — 5M

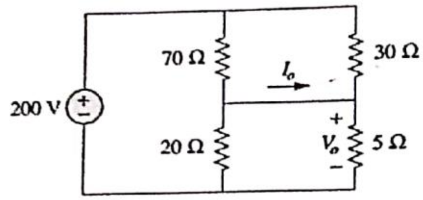


Figure 1

b. Explain in detail the volt-ampere relationship of R, L and C elements with neat diagrams. — 5M

OR

a. State super position theorem and determine current through 40Ω in the circuit shown in figure 2 using super position theorem. — 5M

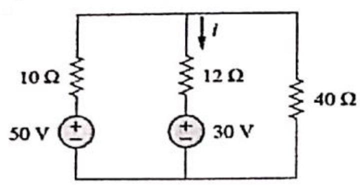


Figure 2

b. Using Thevenin's theorem, find the voltage 'V' in the circuit shown in Figure 3. — 5M

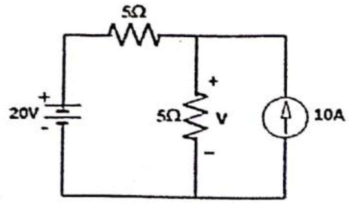


Figure 3

4	a.	Find the rms value, average value and form factor of a sine wave voltage.	5M
	b.	A coil takes a current of 2.5 A at 0.8 lagging power factor from a 220 volt 60 Hz single phase source. If the coil is modeled by a series RL circuit, find i) the complex power in the coil and ii) the value of R and L.	5M
		OR	
5	a.	Obtain the expression for resonant frequency of an RLC series circuit. Also derive the expression for band width.	5M
	b.	Derive an expression for alternating current through an RC series circuit. Draw the phasor diagram for the same.	5M
6	a.	Derive the emf equation of a single-phase transformer.	5M
	b.	Draw and explain the phasor diagram of single phase transformer on load considering with winding resistance.	5M
		OR	
7	a.	Draw the equivalent circuit of a single-phase, 2-winding transformer. Also explain the procedure for obtaining its impedances.	5M
	b.	Explain the working principle of single phase Transformer and also explain the constructional details.	5M
8	a.	Explain the Torque–slip characteristics of a three phase induction motor with a neat diagram.	5M
	b.	Compare between squirrel cage and wound rotor induction motors. Also list their applications.	5M
		OR	
9	a.	Describe with neat sketch the construction and principle of operation of a 3-phase cage type induction motor.	5M
	b.	A 3- phase alternator having 12–poles is driven at a speed of 500 r.p.m. It supplies power to an 8-pole, 3-phase induction motor. If the slip of the motor at full–load is 4%, calculate the full–load speed of the motor.	5M
10	a.	Explain the construction and working of MCB with relevant diagram.	5M
	b.	Discuss types of Batteries and their important characteristics.	5M
		OR	
11	a.	Explain various methods for power factor improvement.	5M
	b.	Draw a neat sketch of plate earthing and estimate the quantity of materials required.	5M

Course Code: 18EE2101

AR18

Geethanjali College of Engineering and Technology (Autonomous), Hyderabad
II B.Tech (CE/ME) I Semester (Regular) End Examinations, Nov/Dec 2019

Time: 3 hours

Basic Electrical Engineering

Answer All Questions

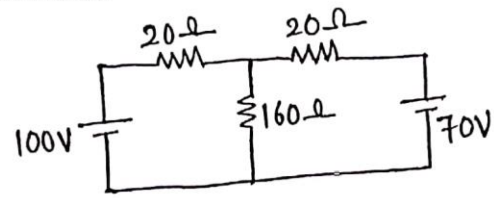
Max. Marks: 70

PART-A 10 X 2M = 20M

1 a. State and Explain KCL and KVL with example
b. Define a) Voltage b) Current.
c. Define resonance
d. Define i) Time Period; ii) Frequency.
e. Enumerate the various losses in Transformer.
f. Write some application of Transformer.
g. Draw the torque speed characteristics of DC Motor.
h. Distinguish between wire and cable.
i. Define a) Power factor b) Reactive Power.
j. List the Components of LT Switchgear.

PART-B 5 X 10M = 50M

2	a.	State and explain super position theorem with example.	5M
	b.	Determine the current through 160 ohm resistance of the network shown below using Thevenin's theorem.	5M



OR

3	a.	Explain in detail the volt ampere relationship of R, L and C elements with neat diagram.	5M
	b.	Obtain transient response of series RL circuit.	5M
4 a		A current of 5A flows through a non- inductive resistance in series with a coil when supplied at 250V, 50 Hz. If the voltage across the resistance is 125V and across the coil is 200V. Calculate Impedance, reactance and resistance of the coil	5M
b		Explain sinusoidal excitation of series RC circuit and draw phasor diagram for the same.	5M
		OR	
5		Derive the average value, r.m.s value and form factor of a purely sinusoidal alternating current.	10M
6a		Derive the expression for EMF in single phase transformer.	5M
b		Define efficiency and regulation of a transformer. Derive condition of maximum efficiency..	5M
		OR	
7a		Explain operation of transformer on load condition with resistive and inductive load.	5M
b		Explain the equivalent circuit of two winding transformer.	5M
8a		Explain the Construction and Working of Synchronous Generator.	5M
b		Explain the various losses in a DC Motor.	5M
		OR	
9		Explain the construction and working of 3 phase induction motor.	10M
10a		Explain the various types of Batteries.	5M
b		Classify different methods of Earthing. Explain any one in detail.	5M
		OR	
11a		Explain the methods to improve the power factor.	5M
b		Explain the components of LT Switchgear.	5M

15. <u>QUESTION BANK</u>

UNIT 1

1.Define the following:

(a) Voltage

(b) Current

(c) Energy

(d) Electric Power

(c) EMF

2. Explain briefly about the conductors, semiconductors and insulation?

3. Explain about basic circuit component?

4. State and explain Ohms law? What are its limitations?

5. State and explain Kirchoff's laws with example?

6. A wire has a resistance of 6ohms. What will be the resistance of another wire of the same material, three times a long and one half the cross sectional area?

7. Define the following:
(a) Circuit element
(b) Active elements and Passive elements
(c) Linear and nonlinear elements

8. Explain the types of energy sources?

9. Derive the expression for equivalent resistance when (i) resistors connected in series
(ii) resistors connected in parallel

10. Derive the expression for equivalent inductance of two inductors connected in series?

5. Derive the expression for equivalent inductance of two inductors connected in parallel?

6. Derive the expression for equivalent capacitance of two capacitors connected in series?

7. Derive the expression for equivalent capacitance of two capacitors connected in parallel?

8. Derive the expression for equivalent inductance of two inductors connected in series?

9. State and explain Thevenin's Theorem

11.State and explain Superposition Theorem

<u>UNIT 2</u>

1.Define the following:

(a) Frequency

(b) Amplitude

(c) Instantaneous Value

(d) Periodic time

(e) Cycle

2. Define and derive average value of alternating current?

3. Define and derive R.M.S value of alternating current?

4. Define form factor, peak factor and power factor?

5. Define Inductive Reactance and explain its variation with frequency?

6. Define Capacitive Reactance and explain its variation with frequency?
7. Define active power, reactive power and apparent power?

8. Derive the expression for current, phase angle, power and power factor for R.C series circuits

9. Derive the expression for current, phase angle, power and power factor for R.L series circuits

10. Derive the expression for current, phase angle, power and power factor for R.L.C series Circuits

11.A Capacitance of 40micro farad and a resistance of 125ohm are connected in series across 200V, 50Hz mains. Find (i) Impedance (ii) current (iii) power factor (iv) phase angle (v) power consumed

12. A resistance of 12ohm, an inductance of 0.15H and a capacitance of 100micro farad are connected in series across 200V, 50Hz supply. Calculate (a) current (b) power factor of the circuit (c) voltage drop across the resistance, inductance and capacitance.

UNIT 3

1. What is a transformer? How does it transfer electric energy from one circuit to another?
2. Explain the basic principle of operation of single phase transformer?
3. Discuss the constructional details of a single phase transformer?
4. Explain the various types of transformers?
5. Explain about shell type and core type transformers?
6. Draw and explain equivalent circuit of a single phase transformer?
7. Derive EMF equation of a transformer?
8. Write differences between Ideal transformer and practical transformer?
9. Discusss the various losses in a transformer?

10. Define efficiency and voltage regulation of a single phase transformer and also derive an expression for voltage regulation?

11. A 6600/600V, 50Hz, single phase transformer has a maximum flux density okf 1.35Wb/sq.m in its core. If the net cross sectional area of the iron core is 200 sq.cm. Calculate the number of turns in the primary and secondary winding of the transformer.

UNIT 4

1. Explain the principle of operation of a D.C. motor?
2. Describe the constructional details of a d. C motor with neat diagram?
3. Derive voltage equation of a DC motor?
4. Explain the various types of DC motors?
5. Explain the various losses in a DC machine?
6. A 220V d.c shunt motor has an armature resistance of 0.5ohm. If full load armature current is 25A and the no-load armature is 3A. Find the change in back EMF from no load to full load.
7. A 230V d.c shunt motor takes 32A at full load. Find back EMF on full load if the resistance of motor armature and shunt field windings are 0.2ohm and 115ohm respectively.
8. A 250V d.c motor takes an armature current of 60A when its speed is 800r.p.m. If the armature resistance is 0.2ohm, Calculate the torque produced .
9. Derive torque equation of a d.c. motor?
10. The armature of a 4 pole d.c shunt motor has a lap winding accommodated in 60slots, each slot containing 20 conductors. If the useful flux per pole be 20mWb, Calculate the total torque developed when the armature current is 50A.

3 phase Induction Motors

1. Explain the principle of 3 phase induction motor?
2. Explain the constructional details of 3 phase induction motor?
3. What is meant by slip of a 3 phase induction motor?
4. Explain the various types rotors of 3 phase induction motor ?
5. Explain how rotating magnetic field is produced in a 3-phase induction motor?
6. Draw and explain equivalent circuit of a single phase transformer?
7. Derive torque equation of a3 phase induction motor?

8. A 3 phase 6 pole induction motor is supplied from a 50Hz, 400V supply. Calculate
(a) The synchronous speed and (b) the speed of the rotor when slip is 4%.

9. If a 6-pole motor from a 50Hz supply an EMF in the rotor of frequency 25Hz. Determine

(a) The slip and (b) the speed of the motor?

10. A 3 phase induction motor is wound for 4 pole and is supplied from 50Hz system. Calculate

(i) the synchronous speed (ii) the speed of the rotor when slip is 4% and (iii) the rotor frequency when rotor runs at 600 rpm.

UNIT 5

1) Explain

A) SFU

B) MCB

c) ELCB

D) MCCB

2) Explain types of wires

3) Explain types of cables

4) Explain earthing

5) Explain types of batteries

6) Explain characteristics of batteries

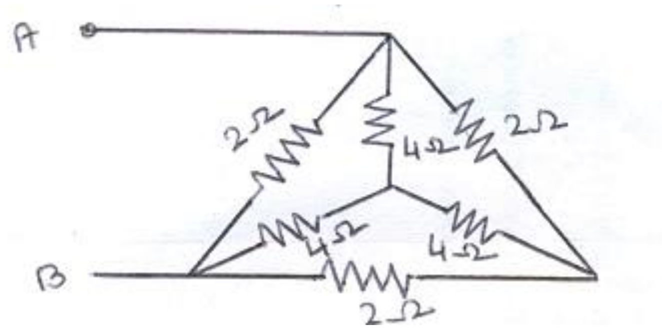
7) Explain how to calculate energy consumption

16. <u>Assignment topics</u>

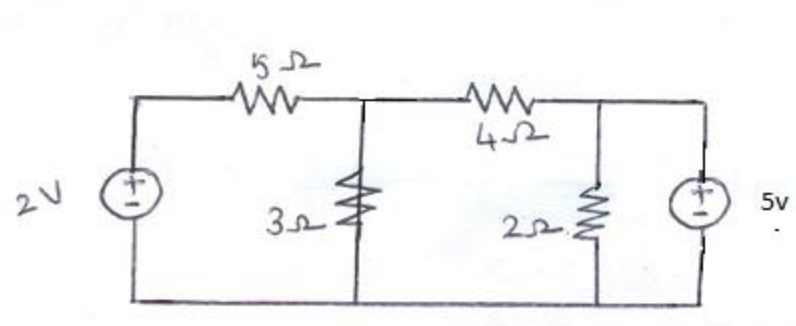
UNIT-1

1. State and explain KVL & KCL.

2. By using network reduction technique, find the resistance across AB Terminal.

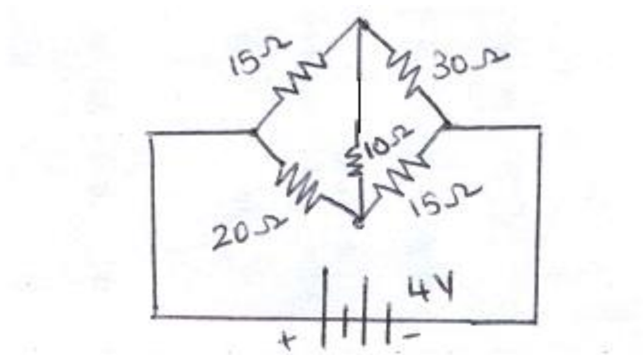


3. For the given circuit find the current flowing through 2Ω resistance using KVL.



4. Explain the Basic circuit components of Electrical Network

5. For the circuit as shown in figure, determine the current flowing through 10Ω resistor using KVL.



UNIT-2

1. Explain sinusoidal excitation for the Elements L and C and also draw the Phasor diagrams.

2. Derive the expression for RMS, Average value, Form factor and peak factor for given sinusoidal voltage V (t) =$V_m$sinwt

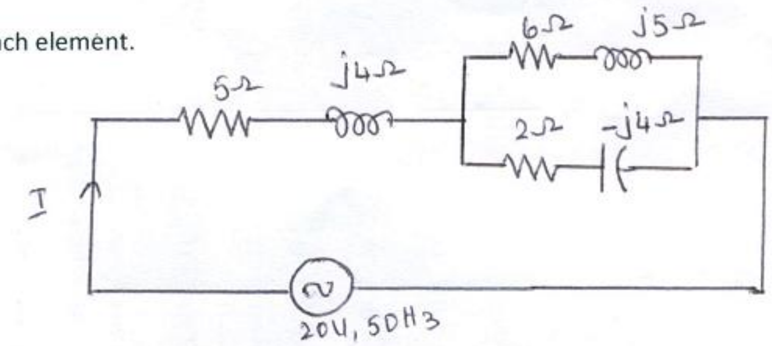
3. For the given circuit .Determine

I) Impedance

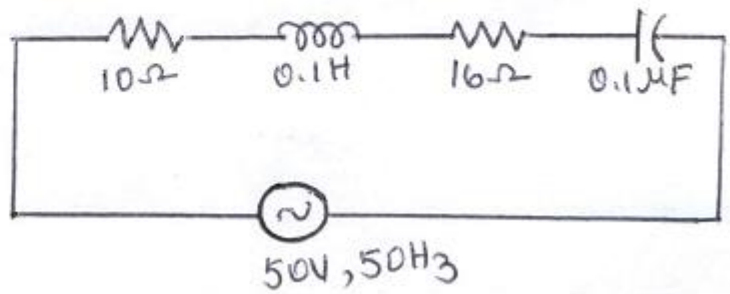
II) Current

III) Power factor

IV).Voltage across each element.



4. In the given circuit, determine I). Impedance II).Current III).Voltage across each element.



UNIT 3

1. Derive the E.M.F expression for a single -phase transformer.
2. Explain the working principle of a single phase transformer with neat diagram.
3. Explain the concept of Ideal transformer and Practical Transformer. Draw the Phasor diagram.
4. A single phase transformer has 500 turns on primary and 50 turns on secondary winding. The no-load current is 1.0A at a p.f of 0.2. The power drawn on no-load is 50W.Calculated the voltage across the primary and secondary windings, the active and reactive component of the current and flux density in core, if area of cross section is $0.004m^2$ and frequency is 50Hz.
5. Explain the types of transformers based on their construction with neat diagrams.

UNIT 4

1.(i) Draw a detailed sketch of a D.C. machine and identify the different parts. Briefly explain the function of each major part.

(ii) Derive the expression for torque of a d.c.motor.

2.(i). Explain with help of suitable diagrams how rotating magnetic field is produced in a three phase induction motor.

3.(i) A 250V, d.c .shunt motor takes a line current of 20A.resistance of shunt field winding is 200Ω and resistance of the armature is 0.3Ω.Find the armature current and the back e.m.f.

(ii) A three phase induction motor is wound for 4 poles and supplied from 50Hz system. Calculate synchronous speed, rotor speed when slip is 4% and rotor frequency when rotor runs at 600rpm.

4(i) A 4 pole generator having wave wound armature winding has 48 slots, each slot contains 20 conductors. What will be the voltage generated in a machine when driven at 1500 rpm? Assume the flux per pole is 7mwb.

(ii) Explain the classification of D.C. Motor with neat diagrams and their voltage equations.

5(i) Explain the working principle of three phase induction motor.

UNIT 5

1)Explain

a)SFU

b)MCB

c)ELCB

d)MCCB

2)Explain types of wires

3)Explain types of cables

4)Explain earthing

5)Expalin types of batteries

6)Explain characteristics of batteries

7)Explain how to calculate energy consumption

17. UNIT WISE QUIZ QUESTIONS

UNIT 1

1 What is the name for the flow of electrons in an electric circuit?

- A. Voltage
- B. Resistance
- C. Capacitance
- **D**. Current

2 What is the basic unit of electric current?

- A. The volt
- B. The watt
- **C**. The ampere
- D. The ohm

3 Which instrument would you use to measure electric current?

- A. An ohmmeter
- B. A wavemeter
- C. A voltmeter
- **D**. An ammeter

4 What is the name of the pressure that forces electrons to flow through a circuit?

- A. Magnetomotive force, or inductance
- **B**. Electromotive force, or voltage
- C. Farad force, or capacitance
- D. Thermal force, or heat

5 What is the basic unit of electromotive force (EMF)?

- **A**. The volt
- B. The watt
- C. The ampere
- D. The ohm

6 How much voltage does an automobile battery usually supply?

- **A**. About 12 volts
- B. About 30 volts
- C. About 120 volts
- D. About 240 volts

7 How much voltage does a wall outlet usually supply (in the US)?

- A. About 12 volts
- B. About 30 volts
- **C**. About 120 volts
- D. About 480 volts

8 Which instrument would you use to measure electric potential or electromotive force?

- A. An ammeter
- **B**. A voltmeter
- C. A wavemeter
- D. An ohmmeter

9 What limits the current that flows through a circuit for a particular applied DC voltage?

- **A**. Reliance
- B. Reactance
- C. Saturation
- D. Resistance

10 What is the basic unit of resistance?

- A. The volt
- B. The watt
- C. The ampere
- **D**. The ohm

11 Which instrument would you use to measure resistance?

- A. An ammeter
- B. A voltmeter
- C. An ohmmeter
- D. A wavemeter

12 What are three good electrical conductors?

- A. Copper, gold, mica
- B. Gold, silver, wood
- **C**. Gold, silver, aluminum
- D. Copper, aluminum, paper

13.The concept on which Superposition theorem is based is

- reciprocity
- duality
- non-linearity
- linearity

14.Kirchhoff s law is applicable to

- passive networks only
- AC circuits only
- DC circuits only
- both AC as well DC circuits

15.Kirchhoff s law is not applicable to circuits with

- lumped parameters
- passive elements
- distributed parameters
- non-linear resistances

16. Which of the following is non-linear circuit parameter?

- Inductance
- Condenser
- Wire wound resistor
- Transistor

17.An ideal voltage source should have

- large value of e.m.f.
- small value of e.m.f.
- zero source resistance
- infinite source resistance

18. According to Kirchhoff’s voltage law, the algebraic sum of all IR drops and EMF. in any closed loop of a network is always

- negative
- positive
- Determined by battery e.m.fs.
- zero

19.Kirchhoffs voltage law is related to

- junction currents
- Battery e.m.fs.
- IR drops

20.Superposition theorem can be applied only to circuits having

- resistive elements
- passive elements
- non-linear elements
- linear bilateral elements

UNIT 2

[1] In ac circuit, the ratio of kW/kVA is
A. power factor
B. form factor
C. load factor
D. diversity factor

[2] The unit of inductance is
A. Mho
B. henry
C. ohm
D. farad

[3] What is the angular frequency of the ac signal having a frequency of 50Hz
A. 314 rad/s
B. 11,120 rad/s
C. 282 rad/s
D. Data insufficient

[4] Thevenin's equivalent circuit consists of
A. series combination of Rth, Eth, Rl
B. series combination of Rth, Eth
C. parallel combination of Rth, Eth, Rl
D. parallel combination of Rth, Eth

[5] The frequency of DC supply is
A. 16 2/3 Hz
B. 60 Hz
C. 50 Hz
D. 0 Hz

[6] The rms value of sinusoidal 100V peak to peak is
A. 100 V
B. 50/√2 V

C. 50 V
D. 100/√2 V

[7] Which of the following bulbs will have the least resistance?
A. 220V, 60W
B. 220V, 100W
C. 115V, 60W
D. 115V, 100W

[8] The power factor of d.c circuit is always

A. 0
B. unity
C. Less than unity
D. Greater than unity

[9] When an alternating current passes through a pure resistance the electrical power converted in to heat is
A. True power
B. Reactive power
C. Apparent power
D. None of the above

[10] In a pure capacitive circuit if the supply frequency is reduced to half the current will be?
A. doubled
B. Reduced to one fourth
C. Reduced by half
D. None of the above

[11] Which of the following circuit will have zero power factor?
A. Inductance
B. Capacitance
C. Resistance
D. None of the above

[12] For a triangular wave, the form factor is?
A. 1.12
B. 1.15
C. 1.11
D. 1.05

UNIT 3

1. In a transformer

   (a) All turns are equally insulated (b) The end turns are more strongly insulated

   (c) The end turns are closely wound (d) The end turns are widely separated

2. Laminated insulations coated with varnish are normally used in the transformer

   (a) To reduce reluctance of magnetic path

(b) To reduce the effect of eddy current

(c) To increase the reluctance of magnetic path

(d) To reduce the hysteresis effect

3. The required thickness of lamination in a transformer decreases when
   (a) The applied frequency increases (b) The applied frequency decreases

   (c) The applied voltage increases (d) The applied voltage decreases

4. Oil in transformer is used to
   (a) Transfer electrical energy (b) Insulate the windings

   (c) Cool the windings (d) None of the above

5. The windings of a transformer are divided into several coils because

   (a) It is difficult to wind as one coil (b) It reduces voltage per coil

   (c) It requires less insulation (d) None of the above

6. The size and construction of bushings in a transformer depend upon the

   (a) Size of winding (b) Size of tank

   (c) Current flowing (d)Voltage supplied

7. Transformer humming sound is reduced by the

   (a) Proper bracing of transformers assemblies

   (b) Proper insulation

   (c) Proper design

   (d) Proper design of winding

8. Sludge in transformer oil is due to

   (a) Decomposition of oil (b) Decomposition of insulation

(c) Moisture content in oil (d) None of the above

9. A transformer used only for electrical isolation between two circuits has turns ratio which is

(a) More than unity (b) Less than unity (c) Equal to unity (d) More than 0.5

10. If 90 per cent of normal voltage and 90 per cent of normal frequency are applied to a transformer, the per cent charge in hysteresis losses will be

(a) 20% (b) 4.7% (c) 19% (d) 21%

11. If 110 per cent of normal voltage and 110 per cent of normal frequency is applied to a transformer, the percentage change of eddy current losses will be

(a) 10% (b) 20% (c) 25% (d) 21%

12. A transformer has two 2,400 V primary coils and two 240 V coils. By proper connection of the windings, the transformation ratio that can be obtained is

(a) 10 (b) 5 (c) 20 (d) 9

13. A single-phase, 2,200/200 V transformer takes 1 A at the *HT* side or no load at a power factor of 0.385 lagging. The iron losses are

(a)167W (b) 77 W (c) 88 W (d) 98 W

UNIT 4

1. Torque development in a dc motor depends on:

a) Magnetic field and radius of armature

b) Current flowing through the armature conductors

c) Active length of the conductors and number of armature conductors

d) All the above

2. The horse power obtained from the motor shaft is called:
a) IHP
b) BHP
c) Useful torque
d) None of the above

3. The efficiency of a dc motor when developing maximum power will be about:
a) 100%
b) 50%
c) Less than 50%
d) More than 50%

4. A dc motor having full load speed of 75 rpm and speed regulation of 10% will have no load speed of:
a) 825 rpm
b) 675 rpm
c) 800 rom
d) 700 rpm

5. The direction of rotation of a dc compound motor can be reversed by interchanging __ connections:
a) Armature
b) Series field
c) Shunt field
d) Armature and series field

6. A DC shunt motor is running at light load, what happens if the field winding gets opened?
a) Motor will stop
b) Motor will burn
c) Motor will make noise
d) Motor will pick up high speed

7. In an electrical motor, the electromagnetic torque developed is:
a) In opposite direction to both load torque and fractional torque
b) In the same direction to the load torque but opposite direction to the fractional torque
c) In the same direction as the load torque and fractional torque
d) In the same direction as the fractional torque but in opposite direction to the load torque

8. In a dc motor, the shaft torque is less than armature torque. This is due to:
a) Eddy current loss
b) Hysteresis loss
c) Stray loss
d) All the above

9. The starting torque of dc shunt motor is:
a) Zero
b) Low
c) High
d) Very high

10. A DC shunt motor may have rising speed-torque characteristics due to:
a) Very high armature circuit resistance
b) Very high field circuit resistance
c) Very high demagnetizing armature resistance
d) Very low demagnetizing armature reaction

11. The dc motor that has poorest speed regulation is:
a) Cumulative compound
b) Differential compound
c) Series
d) Shunt

12. The dc motor that draws almost same power at different loads is:

a) Cumulative compound
b) Differential compound
c) Series
d) Shunt

13. If the supply voltage to a dc shunt motor is increased by 15%, which of the following will reduce?
a) Full load current
b) Full load speed
c) Starting torque
d) None of the above

14. When the torque of dc series motor is tripled, the power approximately increases by:
a) 33%
b) 50%
c) 75%
d) 150%

15. The speed of dc shunt motor can be increased above its normal speed by:
a) Increasing the field current
b) Decreasing the field current
c) Decreasing the terminal voltage
d) Increasing the armature resistance

<u>Induction Motors</u>

1.Regarding skewing of motor bars in a squirrel cage induction motor, which statement is false ?
(a) it prevents cogging
(b) it increases starting torque
(c) it produces more uniform torque
(d) it reduces motor 'hum' during its operation.

2. The principle of operation of a 3-phase. Induction motor is most similar to that of a
(a) synchronous motor
(b) repulsion-start induction motor
(c) transformer with a shorted secondary
(d) capacitor-start, induction-run motor.

3. The magnetising current drawn by transformers and induction motors is the cause of their ....power factor.
(a) zero
(b) unity
(c) lagging
(d) leading.

4. The effect of increasing the length of air-gap in an induction motor will be to increase the
(a) power factor
(b) speed
(c) magnetising current
(d) air-gap flux.

5. In a 3-phase induction motor, the relative speed of stator flux with respect to ....is zero.

(a) stator winding
(b) rotor
(c) rotor flux
(d) space.

6. An eight-pole wound rotor induction motor operating on 60 Hz supply is driven at 1800 r.p.m. by a prime mover in the opposite direction of revolving magnetic field. The frequency of rotor current is
(a) 60 Hz
(b) 120 Hz
(c) 180 Hz
(d) none of the above.

7. A 3-phase, 4-pole, 50-Hz induction motor runs at a speed of 1440 r.p.m. The rotating field produced by the rotor rotates at a speed of .... r.p.m... with respect to the rotor.
(a) 1500
(b) 1440
(c) 60
(d) 0.

8. In a 3-□ induction motor, the rotor field rotates at synchronous speed with respect to
(a) stator
(b) rotor
(c) stator flux
(d) none of the above.

9. Irrespective of the supply frequency, the torque developed by a SCIM is the same whenever .... is the same.
(a) supply voltage
(b) external load
(c) rotor resistance
(d) slip speed.

10. In the case of a 3-ö induction motor having Ns = 1500 rpm and running with s = 0.04
(a) revolving speed of the stator flux is space is .....rpm
(b) rotor speed is ....rpm
(c) speed of rotor flux relative to the rotor is ....rpm
(d) speed of the rotor flux with respect to the stator is ....rpm.

11. The number of stator poles produced in the rotating magnetic field of a 3-ö induction motor having 3 slots per pole per phase is
(a) 3
(b) 6
(c) 2
(d) 12

12. The power factor of a squirrel-cage induction motor is
(a) low at light loads only
(b) low at heavy loads only
(c) low at light and heavy loads both
(d) low at rated load only.

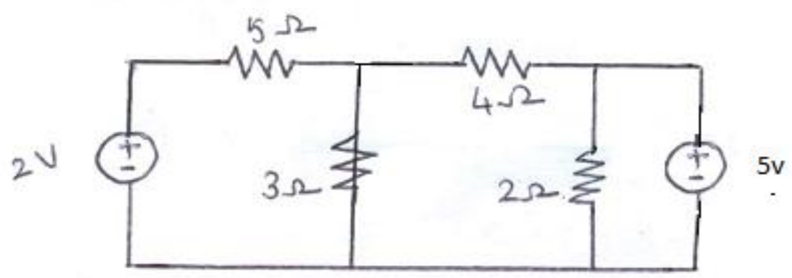
13. Which of the following rotor quantity in a SCIM does NOT depend on its slip ?
(a) reactance
(b) speed
(c) induced EMF
(d) frequency.

14. A 6-pole, 50-Hz, 3-ö induction motor is running at 950 rpm and has rotor Cu loss of 5 kW. Its rotor input is ......kW.
(a) 100
(b) 10
(c) 95
(d) 5.3

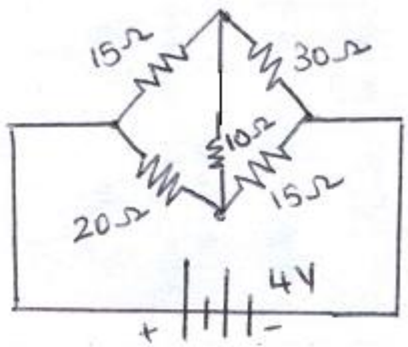
Unit 5
1) The fuse blows off by ____________
(a) Arcing (b) Burning (c)Melting (d) None
2) A material best suited for the manufacture of the fuse is
(a) Silver (b) Copper (c) Aluminium (d) Zinc
3) The ground wire is coloured in ________
4) The neutral wire is coloured in __________
5) The maximum value of power factor Cn BE
(a) 0.8 (b) 0.8 (c) 1 (d)infinity
6) The primary cell generally used for
(a) wall clocks (b)aeroplanes (c)trains (d)automobiles
(7) The lagging power factor is due to ___________ power drawn by the circuit
(a)active (b)reactive (c)apparent (d)none
(8)The positive plate of lead acid cell is ______________
(9)In equipment grounding the enclosure is connected to ______ wire
(a)ground (b) neutral (c)both (d) none
(10)A fuse in motor circuit provides protection gainst
(a)short circuit (b)over load (c)open circuit (d)both short circuit and overload

18. TUTORIAL PROBLEMS

Unit 1
1 Explain superposition theorem
2. For the given circuit find the current flowing through 2Ω resistance using KVL.



3. For the circuit as shown in figure, determine the current flowing through 10Ω resistor using KVL.

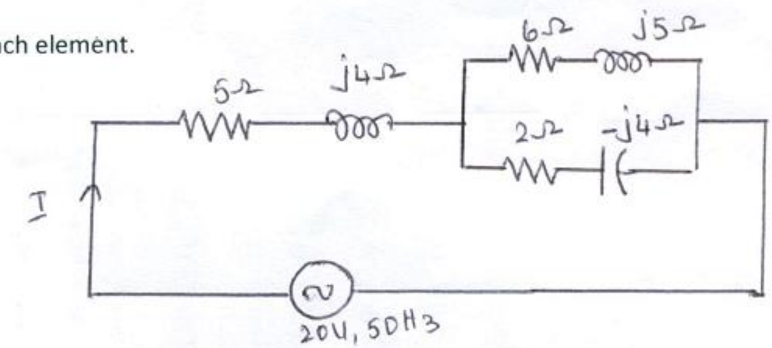


UNIT-2

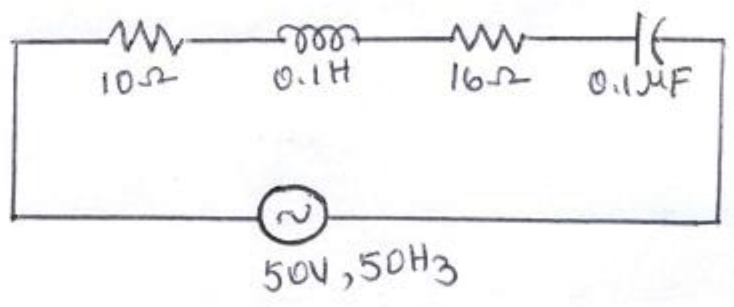
1. Derive the expression for RMS, Average value, Form factor and peak factor for given sinusoidal voltage V (t) =$V_m$sinwt

2) For the given circuit .Determine
 I) Impedance
II) Current
III) Power factor

IV).Voltage across each element.



3. In the given circuit, determine I). Impedance II).Current III).Voltage across each element.



UNIT 3

1.A single phase transformer has 500 turns on primary and 50 turns on secondary winding. The no-load current is 1.0A at a p.f of 0.2. The power drawn on no-load is 50W.Calculated the voltage across the primary and secondary windings, the active and reactive component of the current and flux density in core, if area of cross section is 0.004m^2 and frequency is 50Hz.

2)A 6600/600V, 50Hz, single phase transformer has a maximum flux density okf 1.35Wb/sq.m in its core. If the net cross sectional area of the iron core is 200 sq.cm. Calculate the number of turns in the primary and secondary winding of the transformer.

3)Derive EMF equation of transformer

4)Explain equivalent circuit of transformers

UNIT 4

1 A 250V, D C .shunt motor takes a line current of 20A.resistance of shunt field winding is 200Ω and resistance of the armature is 0.3Ω.Find the armature current and the back e.m.f.

2. A three phase induction motor is wound for 4 poles and supplied from 50Hz system. Calculate synchronous speed, rotor speed when slip is 4% and rotor frequency when rotor runs at 600rpm.

Explain the classification of D.C. Motor with neat diagrams and their voltage equations.

3.Derive torque equation of DC Motor

19. <u>Known gaps</u>

No gaps

20. DISCUSSION TOPICS

Unit -1

- ❖ KVL, KCL
- ❖ Ohms Law
- ❖ Basic circuit elements
- ❖ Network Reduction Techniques
- ❖ Supersposition, Thevenenin's and Norton's Theorem

Unit -2

- ❖ Time period, frequency and cycle
- ❖ Average Value, rms value
- ❖ Form factor, Peak factor
- ❖ RL series circuit, RC series circuit and RLC series circuit

Unit -3

- ❖ Faradays laws of Electromagnetic induction
- ❖ Construction of Transformer
- ❖ Ideal and Practical Transformer
- ❖ Working principle of Transformer
- ❖ Types of transformers
- ❖ Transformer losses
- ❖ Efficiency and Voltage regulation

Unit -4

- ❖ Principle of operation of DC & AC motor
- ❖ Types of DC and AC motors
- ❖ Construction of 3 phase induction motor
- ❖ Torque equation
- ❖ Synchronous generator

Unit -5

- ❖ SFU
- ❖ MCB
- ❖ ELCB
- ❖ MCCB

21. REFERENCES, JOURNALS, WEBSITES AND E-LINKS

Text-Books:

1. Basic Electrical Engineering - D.P. Kothari and I.J. Nagrath, 3rd edition 2010, Tata McGraw Hill.
2. D.C. Kulshreshtha, “Basic Electrical Engineering”, McGraw Hill, 2009.

Reference-Books:

1. L.S. Bobrow, Fundamentals of Electrical Engineering”, Oxford University Press, 2011
2. Electrical and Electronics Technology, E. Hughes, 10th Edition, Pearson, 2010
3. Electrical Engineering Fundamentals, Vincent Deltoro, Second Edition, Prentice Hall India, 1989.

Websites

1.http://www.allelectricals.com

2. http:/www.google.com/fundamentals of electrical

3. http://ocw.mit.edu

22. QUALITY CONTROL SHEETS

Will be collected at the end of the course

23. STUDENT LIST

24. GROUP-WISE STUDENTS LIST FOR DISCUSSION TOPICS