NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE
(NAAC Accredited)
(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)

DEPARTMENT OF MECHATRONICS ENGINEERING

COURSE MATERIALS

EE 100 BASICS OF ELECTRICAL ENGINEERING

VISION OF THE INSTITUTION
To mould true citizens who are millennium leaders and catalysts of change through excellence in education.
MISSION OF THE INSTITUTION
NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values. We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2013
- Course offered: B.Tech Mechatronics Engineering
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

To develop professionally ethical and socially responsible Mechatronics engineers to serve the humanity through quality professional education.

DEPARTMENT MISSION

1) The department is committed to impart the right blend of knowledge and quality education to create professionally ethical and socially responsible graduates.

2) The department is committed to impart the awareness to meet the current challenges in technology.

3) Establish state-of-the-art laboratories to promote practical knowledge of mechatronics to meet the needs of the society

PROGRAMME EDUCATIONAL OBJECTIVES

I. Graduates shall have the ability to work in multidisciplinary environment with good professional and commitment.

II. Graduates shall have the ability to solve the complex engineering problems by applying electrical, mechanical, electronics and computer knowledge and engage in lifelong learning in their profession.

III. Graduates shall have the ability to lead and contribute in a team with entrepreneur skills, professional, social and ethical responsibilities.

IV. Graduates shall have ability to acquire scientific and engineering fundamentals necessary for higher studies and research.

PROGRAM OUTCOME (PO'S)

Engineering Graduates will be able to:

PO 1. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

PO 2. Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO 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.

PO 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.

PO 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.

PO 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.

PO 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.

PO 8. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO 9. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

PO 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.

PO 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.

PO 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 OUTCOME(PSO'S)

PSO 1: Design and develop Mechatronics systems to solve the complex engineering problem by integrating electronics, mechanical and control systems.

PSO 2: Apply the engineering knowledge to conduct investigations of complex engineering problem related to instrumentation, control, automation, robotics and provide solutions.

COURSE OUTCOME

After the completion of the course the student will be able to

CO 1	Solve the elementary concepts of electrical circuits
CO 2	Acquire knowledge in magnetic circuits and ac fundamentals
CO 3	Analysis of single phase and three phase circuits
CO 4	Acquire knowledge in basic power generation systems
CO 5	Understand the working and construction of transformers.
CO 6	Describe about dc machines

CO VS PO'S AND PSO'S MAPPING

CO	PO1	PO 2	PO3	PO 4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PS0 1	PSO 2
CO 1	3	3	2	2	-	-	-	-	-	-	-	3	-	1
CO 2	3	3	2	2	-	-	-	-	-	-	-	3	-	1
CO 3	3	3	2	2	-	-	-	-	-	-	-	3	-	1
CO 4	3	3	2	2	-	-	-	-	-	-	-	3	-	1
CO 5	3	3	2	2	-	-	-	-	-	-	-	3	-	1
CO 6	3	3	2	2	-	-	-	-	-	-	-	3	-	1

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Course No.	Course Name	L-T-P-Credits	Year of Introduction
EE100	BASICS OF ELECTRICAL ENGINEERING	2-1-0-3	2015

Course Objectives

To impart a basic knowledge in Electrical Engineering with an understanding of fundamental concepts.

Syllabus

Elementary concepts of electric circuits, Kirchhoff's laws, constant voltage and current sources, Matrix representation; Magnetic circuits, energy stored in magnetic circuits, Electromagnetic induction, Alternating current fundamentals; AC Circuits, Phasor representation of alternating quantities- rectangular, polar and exponential forms; Three phase systems, star and delta connection; Generation of power, Power transmission and distribution; Transformers, Electric Machines- D.C. Machines, AC Motors; Tariff, Wiring systems, Lamps.

Expected outcome

The course will enable the students to gain preliminary knowledge in basic concepts of Electrical Engineering.

References Books:

- Bhattacharya, S. K., Basic Electrical & Electronics Engineering, Pearson
- Bird, J., Electrical Circuit Theory and Technology, Routledge, Taylor & Francis Group
- Del Toro, V., Electrical Engineering Fundamentals, Prentice Hall of India.
- Hayt, W. H., Kemmerly, J. E., and Durbin, S. M., Engineering Circuit Analysis, Tata McGraw Hill
- Hughes, Electrical and Electronic Technology, Pearson Education
- Mehta, V. K. and Mehta, R., Basic Electrical Engineering, S. Chand Publishing
- Parker and Smith, Problems in Electrical Engineering, CBS Publishers and Distributors
- Sudhakar and Syam Mohan, Circuits and Networks Analysis and Synthesis, Tata McGraw Hill
- Suresh Kumar, K. S, Electric Circuits and Networks, Pearson Education

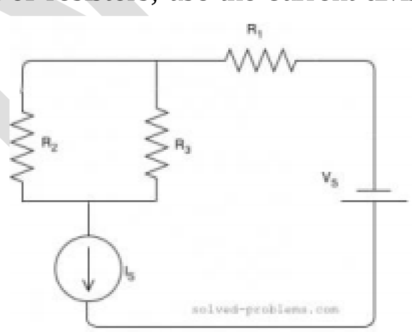
Course Plan

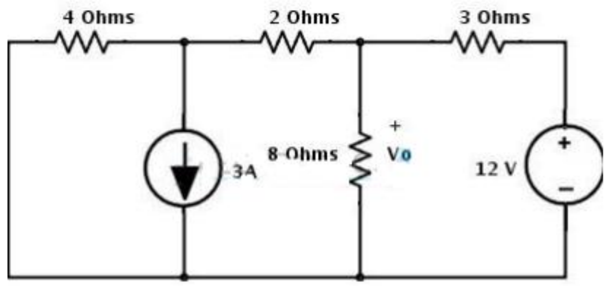
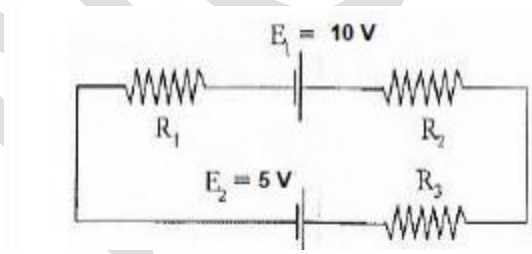
Module	Contents	Hours	Sem. Exam Marks
I	Elementary concepts of electric circuits: Kirchhoff's laws, constant voltage and current sources, formation of network equations by node voltage and mesh current methods. Matrix representation - solution of network equations by matrix methods, star-delta conversion (Analysis of resistive networks only). Numerical problems.	6	15%

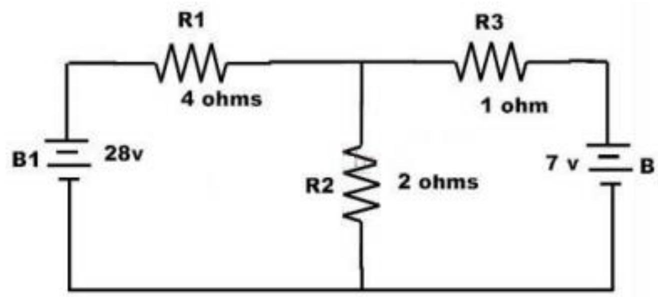
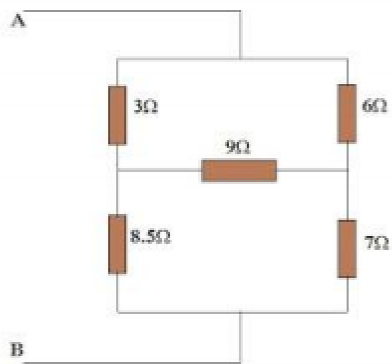
II	Magnetic circuits: MMF, field strength, flux density, reluctance, energy stored in magnetic circuits. Electromagnetic induction: Faraday's laws, Lenz's law-statically induced and dynamically Induced emfs- self-inductance and mutual inductance, coefficient of coupling. Alternating current fundamentals: Generation of alternating voltages, waveforms frequency, period, average and RMS values and form factor. Numerical problems.	9	15%
FIRST INTERNAL EXAM			
III	AC Circuits: Phasor representation of alternating quantities- rectangular, polar and exponential forms. Analysis of simple ac circuits - concept of impedance. Power and power factor in ac circuits- active, reactive and apparent power. Solution of RL, RC and RLC circuits. Three phase systems: Generation of three phase voltages- advantages of three phase systems, star and delta connection, three wire and four wire systems, relation between line and phase voltages, line and phase currents. Three phase power measurement by two wattmeter method. Numerical problems.	9	15%
IV	Generation of power: Block schematic representation of generating stations- hydroelectric, thermal and nuclear power plants. Renewable energy sources. Power transmission and distribution: Typical electrical power transmission scheme, need for high voltage transmission, substation equipments, primary and secondary transmission and distribution systems.	5	15%
SECOND INTERNAL EXAM			
V	Transformers: construction of single phase and three phase transformers (core type only) – EMF equation, losses and efficiency. Electric Machines: D.C. Machines - Construction, types, principles of operation of dc motor, applications. AC Motors - Construction, principles of operation of single phase and three phase induction motor. Principle of operation of Universal motor.	7	20%
VI	Tariff: Different types of LT and HT consumers, tariff schemes - uniform tariff and differential tariff. Wiring systems: Basic concepts of wiring (conduit wiring only), service mains, meter board and distribution board. Earthing of installations - necessity of earthing, plate & pipe earthing, protective fuses, MCB, ELCB. Lamps: Different types of lamps - Incandescent lamps, fluorescent, mercury vapour, sodium vapour, metal halide and LED lamps.	6	20%
END SEMESTER EXAM			

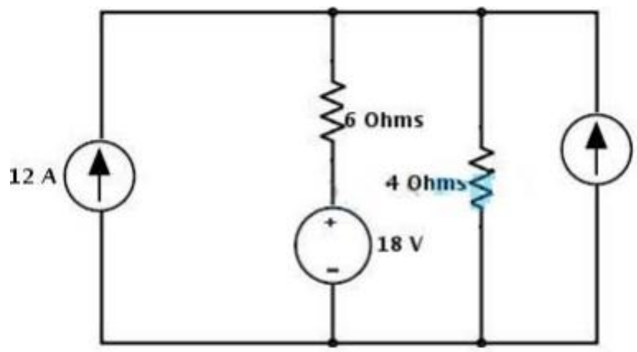
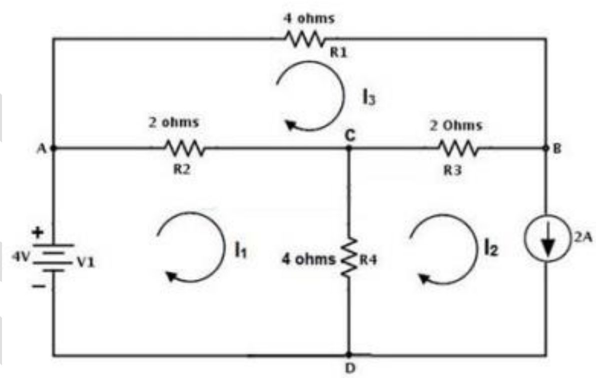
QUESTION BANK

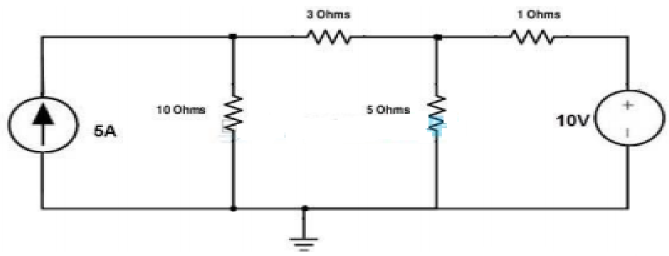
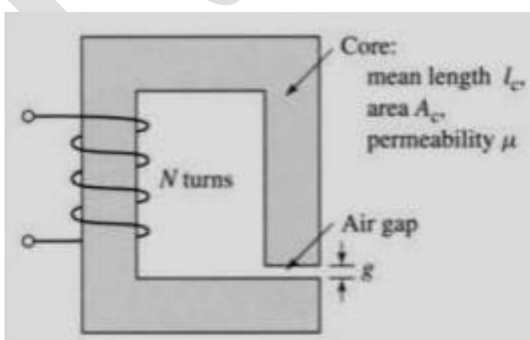
MODULE I

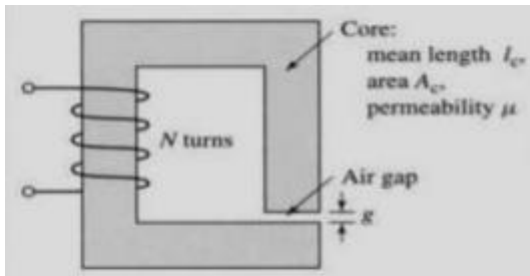
Q:NO:	QUESTIONS	CO	KL
1	Define Electric circuit.	CO1	K1
2	Discuss in detail about the various types of electric networks.	CO1	K2
3	What are the basic properties of electric circuit?	CO1	K1
4	With neat sketch compare unilateral and bilateral circuit.	CO1	K4
5	Discuss in detail about the voltage and current relationships in open, closed and short circuit.	CO1	K2
6	Compare active and passive electrical components with examples.	CO1	K4
7	Elucidate current division rule and voltage division rule with necessary equations.	CO1	K3
8	Find current of resistors, use the current division rule.  	CO1	K2
9	Discuss in detail about the concept of source transformation with necessary sketches and equations.	CO1	K2

10	Consider the below voltage source circuit with a voltage of 20 V and a internal resistance of 5 ohms. This circuit is transformed into the current source by placing a resistor of the same value with a current source. What will be the value of current source.	CO1	K2
11	Apply source transformation to simplify the circuit below. 	CO1	K3
12	Interpret the Kirchoff's first and second law with suitable sketches and necessary equations.	CO1	K3
13	Define branch, node, loop and mesh.	CO1	K1
14	List the various applications of KCL and KVL.	CO1	K1
15	If R1 = 2Ω, R2 = 4Ω, R3 = 6Ω, determine the electric current that flows in the circuit below. 	CO1	K4

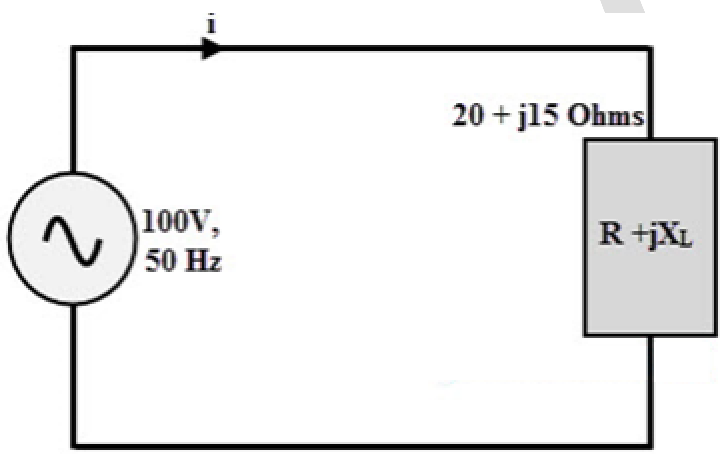
16	Consider the below typical two loop circuit where we have to find the currents I1 and I2 by applying the Kirchhoff‘s laws. 	CO1	K4
17	Discuss the star-Delta transformation and write the transforming equations.	CO1	K2
18	Find the total resistance between A&B terminals for the network shown in figure. 	CO1	K2
19	Discuss in detail about the various steps involved in solving mesh analysis.	CO1	K2

20	Consider the below figure, find the voltage across the 12A current source using mesh analysis. In the given circuit all the sources are current sources. 	CO1	K2
21	Consider the below circuit where we determine the voltage across the current source and a branch current Iac. Assign the directions as shown below and note that current is assigned opposite to the source current in second loop. 	CO1	K4
22	Discuss in detail about the various steps involved in solving node analysis.	CO1	K2

23	Determine the node voltages and currents in each branch using nodal analysis method in the given circuit. 	CO1	K2
MODULE II			
1	Define magnetic circuit.	CO2	K1
2	Investigate in detail about series and parallel magnetic circuit.	CO2	K6
3	Discuss in detail about Magnetic flux, Flux density, Flux intensity, MMF, reluctance and Permeability with necessary equations.	CO2	K2
4	Define leakage flux and fringing in magnetic circuits.	CO2	K1
5	A magnetic circuit with a single air gap is shown in Fig. The core dimensions are: Cross-sectional area Ac = 1.8 × 10-3 m 2 Mean core length lc = 0.6 m Gap length g = 2.3 x 10-3 m N = 83 turns. 	CO2	K4

6	Consider the magnetic circuit of with the dimensions of Problem. Assuming infinite core permeability, calculate (a) the number of turns required to achieve an inductance of 12 mH and (b) the inductor current which will result in a core flux density of 1.0 T. 	CO2	K4
7	Compare electric circuit's vs magnetic circuit.	CO2	K4
8	Define electromagnetic induction and the basic statement behind faradays law of EMI.	CO2	K1
9	Discuss the Flemming's motor rule and generator rule with necessary sketches.	CO2	K2
10	Investigate in detail about the types of induced emf with necessary sketches and equations.	CO2	K6
11	Compare statically induced emf and dynamically induced emf.	CO2	K4
12	Discuss in detail about coefficient of self-inductance, mutual inductance and coefficient of coupling.	CO2	K2
13	A solenoid of 500 turns is wound on an iron core of relative permeability 800. The length and radius of the solenoid are 40 cm and 3 cm respectively. Calculate the average emf induced in the solenoid if the current in it changes from 0 to 3 A in 0.4 second.	CO2	K4
14	The self-inductance of an air-core solenoid is 4.8 mH. If its core is replaced by iron core, then its self-inductance becomes 1.8 H. Find out the relative permeability of iron	CO2	K4

15	Compare AC and DC.	CO2	K4
16	Discuss in detail about the generation of single phase alternating emf.	CO2	K2
17	Define period, frequency, peak value and instantaneous value in a sinusoidal wave form.	CO2	K1
18	Derive rms value and average value for sinusoidal wave.	CO2	K4
19	A sinusoidal alternating current of 6 amps is flowing through a resistance of 40Ω. Calculate the average voltage and the peak voltage of the supply.	CO2	K3
MODULE III			
1	Discuss in detail about the phasor representation of ac.	CO3	K2
2	Define phase and phase difference.	CO3	K1
3	With suitable sketches discuss in detail about in-phase, lagging phase and leading phase.	CO3	K3
4	Discuss in detail about the analysis of purely Resistance circuit.	CO3	K2
5	Discuss in detail about the analysis of purely Inductive and Capacitive circuit.	CO3	K2
6	Discuss in detail about the analysis of R-L circuit.	CO3	K2
7	Discuss in detail about the analysis of R-C circuit.	CO3	K2
8	Discuss in detail about the analysis of series R-L-C circuit.	CO3	K2
9	Discuss in detail about the analysis of parallel R-L-C circuit.	CO3	K2

10	In the circuit shown in Figure the current is 1.8 A. If the current through the capacitor is 1.5 A, find the applied voltage and the resistance of the resistor	CO3	K3
11	Discuss in detail about the types of ac power.	CO3	K2
12	Define power factor.	CO3	K1
13	If an AC power supply of 100V, 50Hz is connected across a load of impedance, 20 + j15 Ohms. Then calculate the current flowing through the circuit, active power, apparent power, reactive power and power factor. 	CO3	K3
14	Discuss in detail about three phase star connected systems and its voltage and current relations.	CO3	K2
15	Discuss in detail about three phase Delta connected systems and its voltage and current relations.	CO3	K2
16	List the various advantages of three phase systems	CO3	K1
17	The input power to a 3-phase a.c. motor is measured as 5kW. If the voltage and current to the motor are 400V and 8.6A respectively, determine the power factor of the system?	CO3	K3
18	Three identical coils, each of resistance 10ohm and inductance 42mH are connected (a) in star and (b) in delta to a 415V, 50 Hz, 3-phase supply. Determine the total power dissipated in each case.	CO3	K3

MODULE IV			
1	With neat sketch discuss hydroelectric power station and, list the major components.	CO4	K2
2	Discuss the role of surge tank in hydroelectric power station.	CO4	K2
3	Describe the various classification of hydroelectric power plant.	CO4	K2
4	List the various advantage of hydroelectric power plant.	CO4	K1
5	With neat sketch discuss Thermal power station and, list the major components.	CO4	K2
6	How can we improve the efficiency of thermal power plant with neat justification.	CO4	K2
7	Compare the advantages and disadvantages of thermal power station.	CO4	K4
8	With neat sketch discuss Nuclear power station and, list the major components.	CO4	K2
9	Compare the advantages and disadvantages of nuclear power station.	CO4	K4
10	List the various sources of renewable energy.	CO4	K1
11	Discuss in detail about the types and importance of renewable energy.	CO4	K2
12	With neat line diagram explain in detail about the electrical generation, transmission and distribution systems	CO4	K3
13	Compare primary and secondary transmission and distribution networks	CO4	K4

MODULE V			
1	With neat sketch explain the construction of DC Machines	CO5	K3
2	Derive equation for back EMF in DC motors	CO5	K5
3	Explain different types of DC Motors according to the excitation method.	CO5	K2
4	Explain back EMF and write the Back EMF equation for DC Motors.	CO5	K2
5	Elucidate in detail about the construction and types of single phase transformers	CO5	K4
6	Define slip and justify at which time the slip should be maximum in 3 phase induction motors	CO5	K2
7	Derive EMF equation of the transformers	CO5	K5
8	Investigate the construction of three phase induction motors and classify its types.	CO5	K5
9	Compare squirrel cage and slip ring induction motor	CO5	K4
10	Discuss in detail about the basic working principle of three phase induction motors.	CO5	K2
11	Narrate the properties of ideal transformer. Sketch its phasor diagram	CO5	K3
12	Briefly explain the losses in a transformer.	CO5	K2
13	Explain in detail with necessary sketch the construction, working principle, emf equation, transformation ratio, and losses in a transformer.	CO5	K2

MODULE VI			
1	Define electric tariff	CO6	K1
2	List the objectives of electric tariff	CO6	K1
3	Investigate in detail about the types of tariff in electrical systems.	CO6	K6
4	Compare simple tariff and flat rate tariff.	CO6	K4
5	Compare block rate tariff and two part tariff	CO6	K4
6	Investigate in detail about the types of electric wiring system and its components.	CO6	K6
7	Discuss in detail about the wiring of the distribution board	CO6	K2
8	Discuss in detail about the need for earthing and its types.	CO6	K2
9	Compare plate, pipe and rod earthing.	CO6	K4
10	Discuss the various types of circuit breakers and justify its importance in electrical systems.	CO6	K2
11	Discuss the various types of lamps in electrical systems.	CO6	K2

APPENDIX 1

CONTENT BEYOND THE SYLLABUS

MODULE I

ELEMENTARY CONCEPTS OF ELECTRIC CIRCUIT

INTRODUCTION

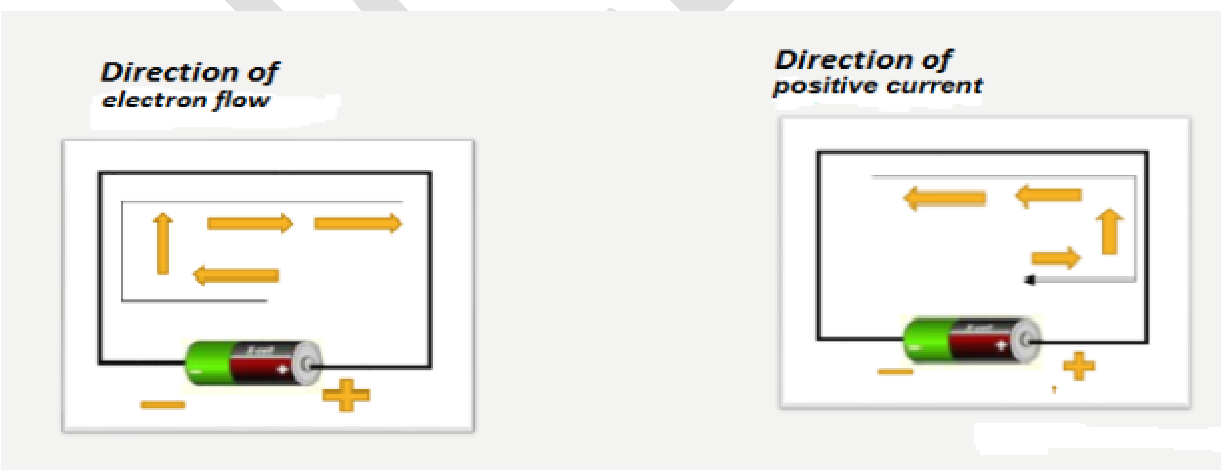
Understanding of electrical terms is compulsory for engineers. As you study electricity in your engineering program, and as you work with electricity in the power plants, industrial plants, you will hear, read, and use various electrical terms. These terms have very exact meanings. You must know what each one means if you are to understand other people and make them understand you. The following terms explain the meaning of the most basic electrical terms.

Electric current the electrical term

Electric current is one of the basic electrical terms described as when electrons flow from one place to another, they make a current. The electrons always flow from a negative point to a positive (or less negative) point, because electrons have a negative charge.

Unfortunately, the direction of the current flow can be confusing. Some people think of a positive current that is in the opposite direction from the electron flow- that is, from positive to negative instead of from negative to positive. You must be careful to distinguish between the two kinds of flow. Both kinds are commonly used in words and diagrams.

The so-called "positive current" is from positive to negative. The "electron flow" is from negative to positive. The word "current" to mean electron flow-from negative to positive. The figure below shows the difference between positive current and electron flow.

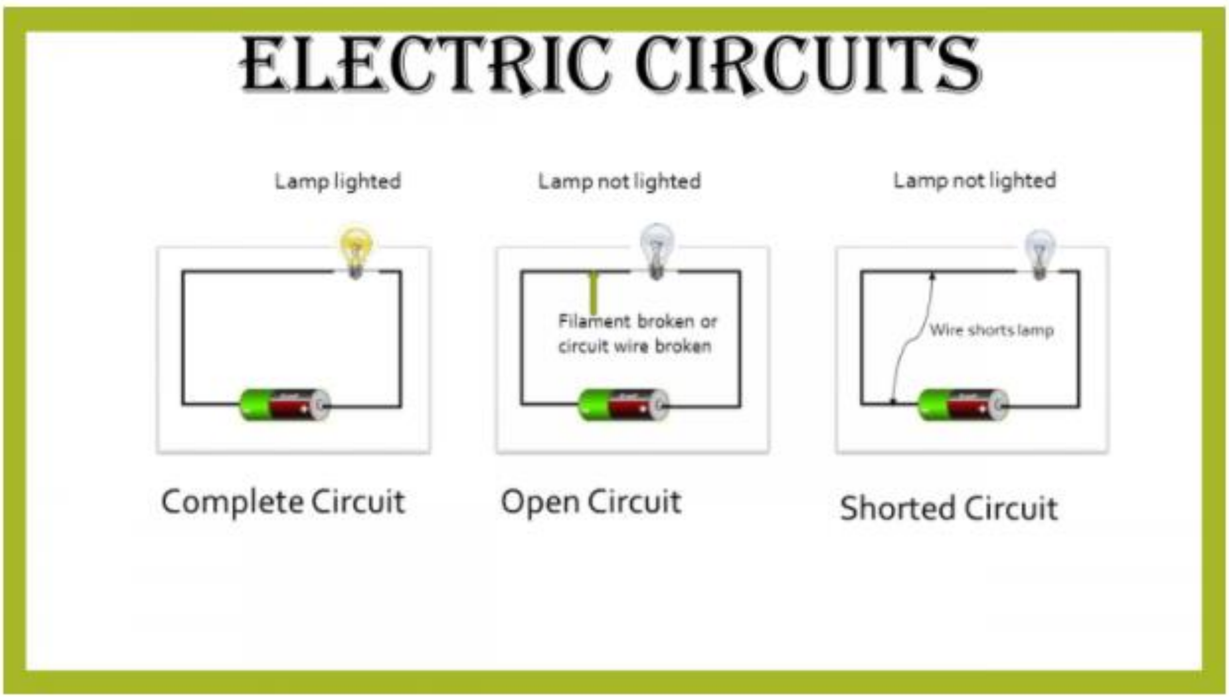


Two directions of electric current

Circuit

Electrons flow along with some kind of path in going from one point to another. This path is called a circuit. If the path has no gaps to stop the flow of electrons, the circuit is said to be complete or closed.

In case the path has a gap that the electrons cannot cross- for example, a break in a wire where the ends are separated by air- the circuit is said to be open. If another pathway provides an easier way a short circuit for the electrons to go from one point another, that part of the circuit is said to be shorted. The figure below shows the circuit that is complete, open, and shorted.



Potential difference

This term is the correct name for what is often called "voltage" or "electromotive force." Potential difference is a measure of how much potential energy an electron has in one place compared to another place.

The greater the potential energy, the more work an electron can do in going from one place to the other. The potential energy of each electron also determines how much current will flow from one point to another in a given circuit.

Resistance

Every electrical pathway from one place to another has the property of resisting the flow of electrons. Some pathways resist the flow only slightly. For example, a thick copper wire offers very little resistance. Other pathways-for examples, an air gap-offer great resistance. The greater the resistance, the less the current for a given potential difference.

Cell

Electricity can be produced by chemical means. The arrangement of materials that produces a potential difference between two points by chemical resources is called a cell. Familiar cells include the dry cells used in flashlights, calculators, and radios.

Battery

When you connect two or more cells together, the combination is called a battery. If your calculator takes two dry cells, the grouping is called a two-cell battery.

The storage battery in a car or truck is usually a six-cell battery that produces a potential difference of 12V between the terminals. Each cell in such a battery produces a potential difference of 2 V between its internal terminals. The terminals of the cells are connected in such a way that their potential differences add together between the external terminals

As you study the remaining lessons in this course and the other courses in your series, make sure you learn the proper terms to use in discussing electricity, and the exact meaning of each term. Always use the correct terms, even if other people do not. If you use the wrong terms, you are likely to be misunderstood. In addition, other people will think you know less about electricity than you actually do.

Alternating Current (AC) — An electric current that reverses its direction many times a second at regular intervals.

Ammeter — An instrument for measuring the flow of electrical current in amperes. Ammeters are always connected in series with the circuit to be tested.

Ampacity — The maximum amount of electric current a conductor or device can carry before sustaining immediate or progressive deterioration.

Ampere-Hour (Ah) — A unit of measure for battery capacity. It is obtained by multiplying the current (in amperes) by the time (in hours) during which current flows. For example, a battery which provides 5 amperes for 20 hours is said to deliver 100 ampere – hours.

Ampere (A) — A unit of measure for the intensity of an electric current flowing in a circuit. One ampere is equal to a current flow of one coulomb per second.

Apparent Power — Measured in volt-ampers (VA). Apparent power is the product of the rms voltage and the rms current.

Armature — The movable part of a generator or motor. It is made up of conductors which rotate through a magnetic field to provide voltage or force by electromagnetic induction. The pivoted points in generator regulators are also called armatures.

Capacitance — The ability of a body to store an electrical charge. Measured in farads as the ratio of the electric charge of the object (Q, measured in coulombs) to the voltage across the object (V, measured in volts).

Capacitor — A device used to store an electric charge, consisting of one or more pairs of conductors separated by an insulator. Commonly used for filtering out voltage spikes.

Circuit — A closed path in which electrons from a voltage or current source flow. Circuits can be in series, parallel, or in any combination of the two.

Circuit Breaker — An automatic device for stopping the flow of current in an electric circuit. To restore service, the circuit breaker must be reset (closed) after correcting the cause of the overload or failure. Circuit breakers are used in conjunction with protective relays to protect circuits from faults.

Conductor — Any material where electric current can flow freely. Conductive materials, such as metals, have a relatively low resistance. Copper and aluminum wire are the most common conductors.

Corona — A corona discharge is an electrical discharge brought on by the ionization of a fluid such as air surrounding a conductor that is electrically charged. Spontaneous corona discharges occur naturally in high-voltage systems unless care is taken to limit the electric field strength.

Current (I) — The flow of an electric charge through a conductor. An electric current can be compared to the flow of water in a pipe. Measured in amperes.

Cycle — The change in an alternating electrical sine wave from zero to a positive peak to zero to a negative peak and back to zero. *See Frequency*.

Demand — The average value of power or related quantity over a specified period of time.

Dielectric constant — A quantity measuring the ability of a substance to store electrical energy in an electric field.

Dielectric strength — The maximum electric field that a pure material can withstand under ideal conditions without breaking down (i.e., without experiencing failure of its insulating properties).

Diode — A semiconductor device with two terminals, typically allowing the flow of current in one direction only. Diodes allow current to flow when the anode is positive in relation to the cathode.

Direct Current (DC) — An electric current that flows in only one direction.

Electrolyte — Any substance which, in solution, is dissociated into ions and is thus made capable of conducting an electrical current. The sulfuric acid – water solution in a storage battery is an electrolyte.

Electromotive Force — (EMF) A difference in potential that tends to give rise to an electric current. Measured in volts.

Electron — A tiny particle which rotates around the nucleus of an atom. It has a negative charge of electricity.

Electron theory — The theory which explains the nature of electricity and the exchange of "free" electrons between atoms of a conductor. It is also used as one theory to explain direction of current flow in a circuit.

Farad — A unit of measure for capacitance. One farad is equal to one coulomb per volt.

Ferroresonance — (nonlinear resonance) a type of resonance in electric circuits which occurs when a circuit containing a nonlinear inductance is fed from a source that has series capacitance, and the circuit is subjected to a disturbance such as opening of a switch. It can cause overvoltages and overcurrents in an electrical power system and can pose a risk to transmission and distribution equipment and to operational personnel.

Frequency — The number of cycles per second. Measured in Hertz. If a current completes one cycle per second, then the frequency is 1 Hz; 60 cycles per second equals 60 Hz.

Fuse — A circuit interrupting device consisting of a strip of wire that melts and breaks an electric circuit if the current exceeds a safe level. To restore service, the fuse must be replaced using a similar fuse with the same size and rating after correcting the cause of failure.

Generator — A device which converts mechanical energy into electrical energy.

Ground — The reference point in an electrical circuit from which voltages are measured, a common return path for electric current, or a direct physical connection to the Earth.

Ground Fault Circuit Interrupters (GFCI) — A device intended for the protection of personnel that functions to de-energize a circuit or portion thereof within an established period of time when a current to ground exceeds some predetermined value that is less than that required to operate the overcurrent protective device of the supply circuit.

Henry — A unit of measure for inductance. If the rate of change of current in a circuit is one ampere per second and the resulting electromotive force is one volt, then the inductance of the circuit is one henry.

Hertz — A unit of measure for frequency. Replacing the earlier term of cycle per second (cps).

Impedance — The measure of the opposition that a circuit presents to a current when a voltage is applied. Impedance extends the concept of resistance to AC circuits, and possesses both magnitude and phase, unlike resistance, which has only magnitude.

Inductance — The property of a conductor by which a change in current flowing through it induces (creates) a voltage (electromotive force) in both the conductor itself (self-inductance) and in any nearby conductors (mutual inductance). Measured in henry (H).

Inductor — A coil of wire wrapped around an iron core. The inductance is directly proportional to the number of turns in the coil.

Insulator — Any material where electric current does not flow freely. Insulative materials, such as glass, rubber, air, and many plastics have a relatively high resistance. Insulators protect equipment and life from electric shock.

Inverter — An apparatus that converts direct current into alternating current.

Kilowatt-hour (kWh) — The product of power in Kw and time in hours. Equal to 1000 Watt-hours. For example, if a 100W light bulb is used for 4 hours, 0.4kWhs of energy will be used (100W x 1Kw / 1000 Watts x 4 hours). Electrical energy is sold in units of kWh.

Kilowatt-hour Meter — A device used to measure electrical energy use.

Kilowatt (Kw) — Equal to 1000 watts.

Load — Anything which consumes electrical energy, such as lights, transformers, heaters and electric motors.

Load Rejection — The condition in which there is a sudden load loss in the system which causes the generating equipment to be over-frequency. A load rejection test confirms that the system can withstand a sudden loss of load and return to normal operating conditions using its governor. Load banks are normally used for these tests as part of the commissioning process for electrical power systems.

Mutual Induction — Occurs when changing current in one coil induces voltage in a second coil.

Ohm — (Ω) A unit of measure of resistance. One ohm is equivilant to the resistance in a circuit transmitting a current of one ampere when subjected to a potential difference of one volt.

Ohm's Law — The mathematical equation that explains the relationship between current, voltage, and resistance (V=IR).

Ohmmeter — An instrument for measuring the resistance in ohms of an electrical circuit.

Open Circuit — An open or open circuit occurs when a circuit is broken, such as by a broken wire or open switch, interrupting the flow of current through the circuit. It is analogous to a closed valve in a water system.

Parallel Circuit — A circuit in which there are multiple paths for electricity to flow. Each load connected in a separate path receives the full circuit voltage, and the total circuit current is equal to the sum of the individual branch currents.

Piezoelectricity — Electric polarization in a substance (especially certain crystals) resulting from the application of mechanical stress (pressure).

Polarity — A collective term applied to the positive (+) and negative (-) ends of a magnet or electrical mechanism such as a coil or battery.

Power — The rate at which electrical energy is transferred by an electric circuit. Measured in Watts.

Power Factor — The ratio of the actual electrical power dissipated by an AC circuit to the product of the r.m.s. values of current and voltage. The difference between the two is caused by reactance in the circuit and represents power that does no useful work.

Protective Relay — A relay device designed to trip a circuit breaker when a fault is detected.

Reactive Power — The portion of electricity that establishes and sustains the electric and magnetic fields of AC equipment. Exists in an AC circuit when the current and voltage are not in phase. Measured in VARS.

Rectifier — An electrical device that converts an alternating current into a direct one by allowing a current to flow through it in one direction only.

Relay — An electrical coil switch that uses a small current to control a much larger current.

Reluctance — The resistance that a magnetic circuit offers to lines of force in a magnetic field.

Resistance — The opposition to the passage of an electric current. Electrical resistance can be compared to the friction experienced by water when flowing through a pipe. Measured in ohms.

Resistor — A device usually made of wire or carbon which presents a resistance to current flow.

Rotor — The rotating part of an electrical machine such as a generator, motor, or alternator.

Self Induction — Voltage which occurs in a coil when there is a change of current.

Semiconductor — A solid substance that has a conductivity between that of an insulator and that of most metals, either due to the addition of an impurity or because of temperature effects. Devices made of semiconductors, notably silicon, are essential components of most electronic circuits.

Series-Parallel Circuit — A circuit in which some of the circuit components are connected in series and others are connected in parallel.

Series Circuit — A circuit in which there is only one path for electricity to flow. All of the current in the circuit must flow through all of the loads.

Service — The conductors and equipment used to deliver energy from the electrical supply system to the system being served.

Short Circuit — When one part of an electric circuit comes in contact with another part of the same circuit, diverting the flow of current from its desired path.

Solid State Circuit — Electronic (integrated) circuits which utilize semiconductor devices such as transistors, diodes and silicon controlled rectifiers.

Transistor — A semiconductor device with three connections, capable of amplification in addition to rectification.

True Power — Measured in Watts. The power manifested in tangible form such as electromagnetic radiation, acoustic waves, or mechanical phenomena. In a direct current (DC) circuit, or in an alternating current (AC) circuit whose impedance is a pure resistance, the voltage and current are in phase.

VARS — A unit of measure of reactive power. Vars may be considered as either the imaginary part of apparent power, or the power flowing into a reactive load, where voltage and current are specified in volts and amperes.

Variable Resistor — A resistor that can beadjusted to different ranges of value.

Volt-Ampere (VA) — A unit of measure of apparent power. It is the product of the rms voltage and the rms current.

Volt (V) — A unit measure of voltage. One volt is equal to the difference of potential that would drive one ampere of current against one ohm resistance.

Voltage — An electromotive force or “pressure” that causes electrons to flow and can be compared to water pressure which causes water to flow in a pipe. Measured in volts.

Voltmeter — An instrument for measuring the force in volts of an electrical current. This is the difference of potential (voltage) between different points in an electrical circuit. Voltmeters have a high internal resistance are connected across (parallel to) the points where voltage is to be measured.

Watt-hour (Wh) — A unit of electrical energy equivalent to a power consumption of one watt for one hour.

Watt (W) — A unit of electrical power. One watt is equivalent to one joule per second, corresponding to the power in an electric circuit in which the potential difference is one volt and the current one ampere.

Wattmeter — The wattmeter is an instrument for measuring the electric power (or the supply rate of electrical energy) in watts of any given circuit.

Waveform — A graphical representation of electrical cycles which shows the amount of variation in amplitude over some period of time.

TYPES OF ELECTRICAL NETWORKS

The interconnection of various active and passive components in a prescribed manner to form a closed path is called an **electric circuit**. The system in which electric current can flow from the source to the load and then back to the other terminal of the source is referred to as an **electric circuit**. The main parts of an ideal **electric circuit** are:

1. Electrical sources for delivering electricity to the circuit and these are mainly electric generators and batteries
2. Controlling devices for controlling electricity and these are mainly switches, circuit breakers, MCBs, and potentiometer like devices etc.
3. Protection devices for protecting the circuit from abnormal conditions and these are mainly electric fuses, MCBs, switchgear systems.
4. Conducting path to carry electric current from one point to other in the circuit and these are mainly wires or conductors.
5. Load.

Thus, voltage and current are the two basic features of an **electric element**. Various techniques by which voltage and current across any element in any electric circuit are determined is called electric circuit analysis.

In this figure shows a simple electric circuit containing

- A battery of 30 V

- A carbon resistor of 5Kω

Due to this, a current I, flows in the circuit and a potential drop of V volts appears across resistor.

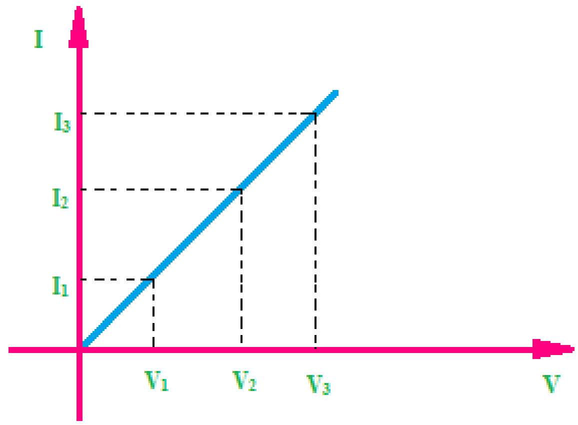
Basic Properties of Electric Circuits

- A circuit is always a closed path.
- A circuit always contains at least an energy source which acts as a source of electrons.
- The electric elements include uncontrolled and controlled source of energy, resistors, capacitors, inductors, etc.
- In an electric circuit flow of electrons takes place from negative terminal to positive terminal.
- Direction of flow of conventional current is from positive to negative terminal.
- Flow of current leads to potential drop across the various elements.

Types of Electrical Circuit:

1. Linear Circuit: When the flow of electrical current through an electrical circuit changes uniformly with the changes of voltage then that circuit is said to be as a Linear circuit. If the circuit is consists of linear elements then the circuit will be Linear.

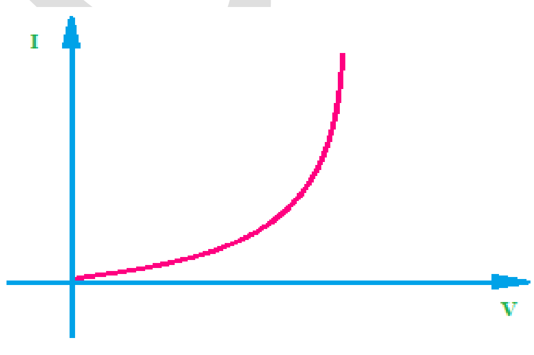
So we can also say if the parameters of an electrical circuit are constant, they do not change with the change of voltage and current then that circuit **is called linear circuit**. Actually, most of the cases the property of an electrical circuit depends on the property of connected elements.



The above diagram shows that the increase of flow of current is uniform to the increase of voltage.

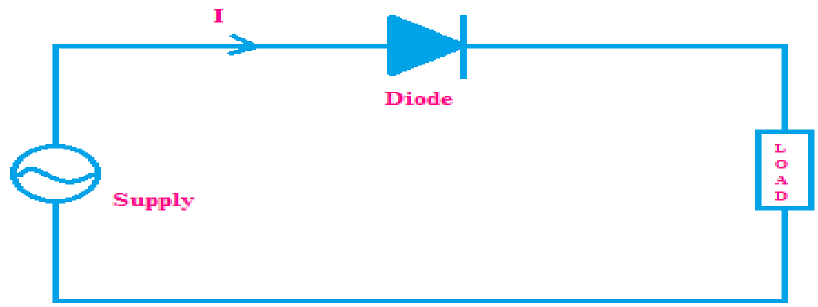
2. Non-linear Circuit: When the flow of current through an electrical circuit changes un uniformly with the changes of voltage then the circuit **is called Non-linear Circuit**.

In the non-linear circuit the parameters are not constant they will change with the change of voltage and current.



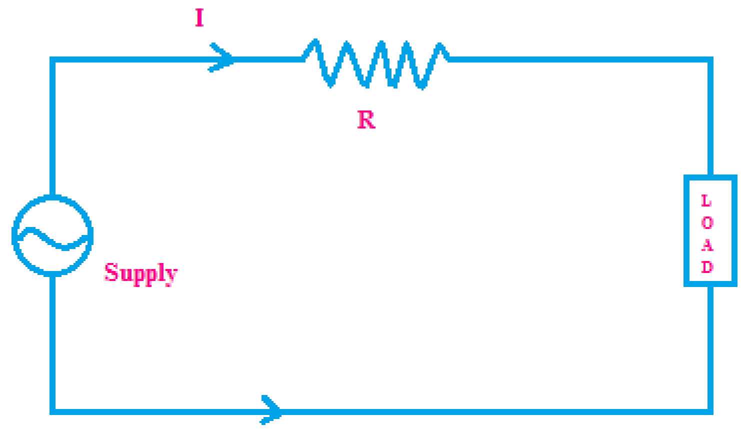
3. Unilateral Circuit: When an electrical circuit changes its properties with the change of the direction of the flow of current then the circuit **is called Unilateral circuit**.

Suppose a resistive circuit whose main function is to oppose the flow of electrical current. If the opposition of the circuit to the flow of current is changed with the change of the direction of flow of current then the circuit is said to be as Unilateral Circuit.



The circuit consisting of Diodes like the rectifier circuit is an **example of Unilateral Circuit**. In this circuit, the current can flow in one direction only because the diode allows the flow of current in one direction only.

4. Bilateral Circuit: If the properties of the electrical circuit do not change with the change of the direction of the flow of current then the circuit **is called Bilateral Circuit**.



The electrical Transmission Line is the **example of a bilateral circuit**.

5. Active Network:

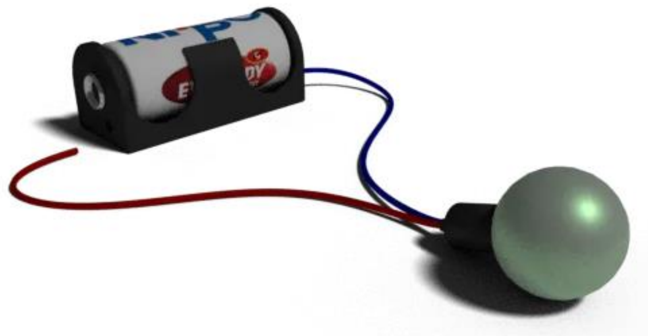
A circuit which contains a source of energy is called **active network**. Voltage and current sources are energy sources.

6. Passive Network:

A circuit which contains no energy source is called **passive network**. The passive network contains resistor, capacitor and inductor.

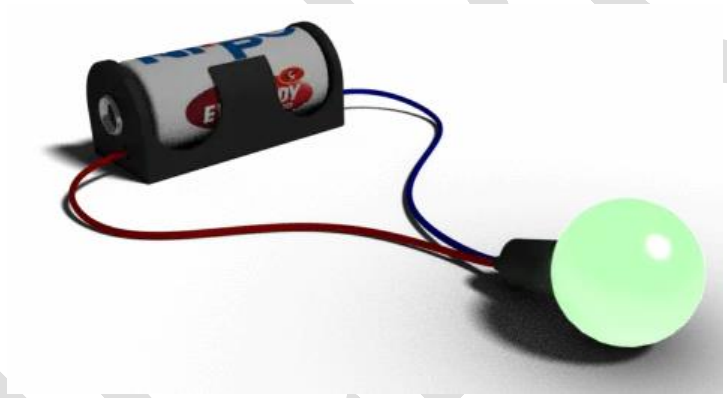
7. Open Circuit

If due to disconnection of any part of an electric circuit if there is no flow of current through the circuit, is said to be an **open circuited**.



8. Closed Circuit

If there is no discontinuity in the circuit and current can flow from one part to another part of the circuit, the circuit is said to be **closed circuit**.



Short Circuit

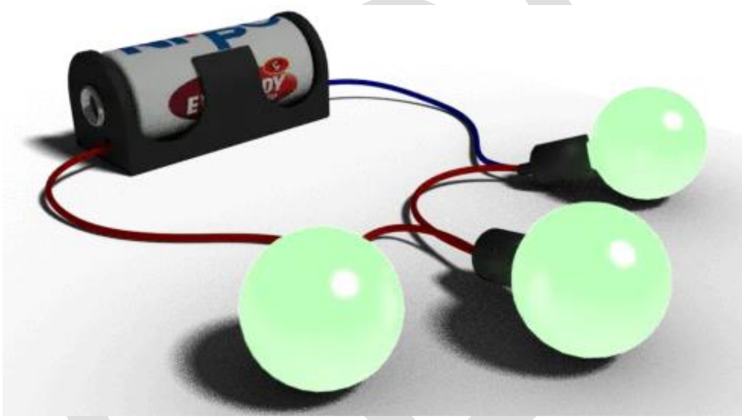
If two or more phases, one or more phases and earth or neutral of AC system or positive and negative wires or positive or negative wires and earth of DC system touch together directly or connected together by a zero impedance path then the circuit is said to be **short circuited**.

Electric circuits can be further categorized according to their structural features into either:

1. **Series Circuits**
2. **Parallel Circuits**
3. **Series Parallel Circuits**

Series Circuit

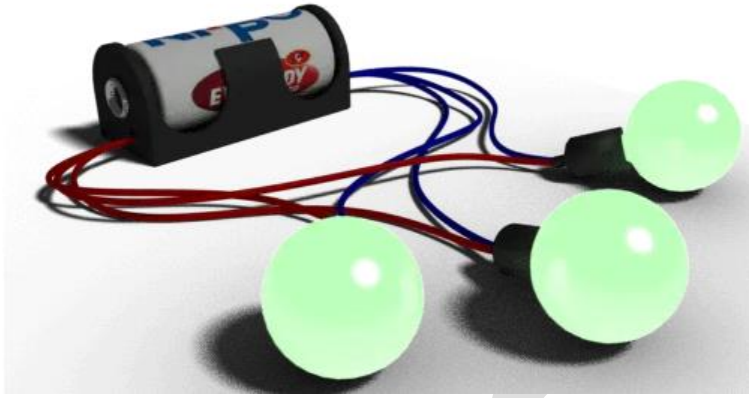
When all elements of a circuit are connected one after another in tail to head fashion and due to which there will be only one path of flowing current then the circuit is called **series circuit**. The circuit elements then are said to be series connected. In the series electrical circuit, same current flows through all element connected in series.



Parallel Circuit

If components are connected in such a way that the voltage drop across each component is same then it is known as **parallel circuit**. In **parallel circuit** the voltage drop across each component is same but the currents flowing through each component may differ. The total current is the sum of currents flowing through each element.

An example of a **parallel circuit** is the wiring system of a house. If one of the electric lamp burns out, current can still flow through the rest of the lights and appliances. In a parallel circuit the voltage is the same for all elements.

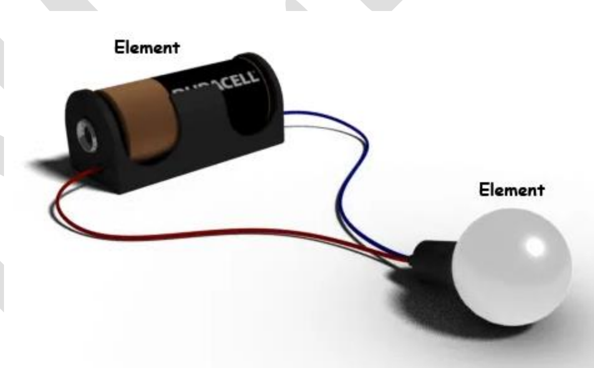


Types of Electronic Components

Electronic elements that make up a circuit are connected together by conductors to form a complete circuit. If these connecting conductors are ideal conductors (i.e. they have no resistance) then all parts of the circuit can be classified into two main categories depending on whether they deliver or absorb energy from the circuit:

- Active components
- Passive components

Electrical symbols are used to represent both active and passive components. An example of a basic circuit made up of two electronic elements has been illustrated below:

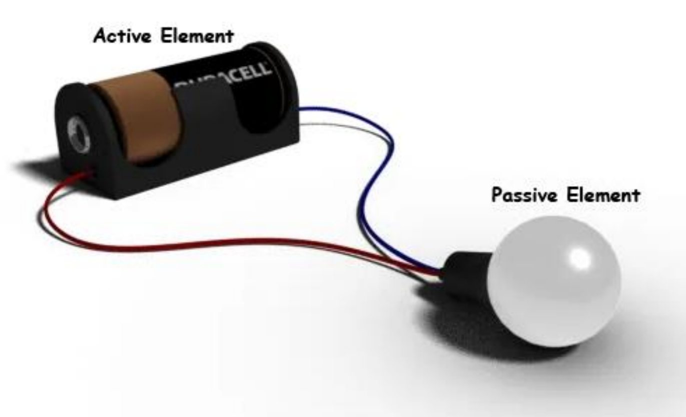


Active Components

An **active component** is an electronic component which supplies energy to a circuit. Active elements have the ability to electrically control electron flow (i.e. the flow of charge). All electronic circuits must contain at least one active component.

Common examples of active components include:

- Voltage sources
- Current sources (e.g. DC current source)
- Generators (such as alternators and DC generators)
- All different types of transistors (such as bipolar junction transistors, MOSFETS, FETs, and JFET)
- Diodes (such as Zener diodes, photodiodes, Schottky diodes, and LEDs)



Voltage Sources

A voltage source is an example of an active component in a circuit. When current leaves from the positive terminal of the voltage source, energy is being supplied to the circuit. As per the definition of an active element, a battery can also be considered as an active element, as it continuously delivers energy to the circuit during discharging.

Current Sources

A current source is also considered an active component. The current supplied to the circuit by an ideal current source is independent of circuit voltage. As a current source is controlling the flow of charge in a circuit, it is classified as an active element.

Transistors

Although not as obvious as a current or voltage source – transistors are also an active circuit component. This is because transistors are able to amplify the power of a signal (see our article on transistors as an amplifier if you want to know exactly how).

As this amplification is essentially controlling the flow of charge – transistors are hence classified as an active component.

Passive Components

A **passive component** is an electronic component which can only receive energy, which it can either dissipate, absorb or store it in an electric field or a magnetic field. Passive elements do not need any form of electrical power to operate.

As the name 'passive' suggests – passive devices do not provide gain or amplification. Passive components cannot amplify, oscillate, or generate an electrical signal.

Common examples of passive components include:

- Resistors
- Inductors
- Capacitors
- Transformers

Resistors

A resistor is taken as a passive element since it can not deliver any energy to a circuit. Instead resistors can only receive energy which they can dissipate as heat as long as current flows through it.

Inductors

An inductor is also considered as passive element of circuit, because it can store energy in it as a magnetic field, and can deliver that energy to the circuit, but not in continuous basis. The energy absorbing and delivering capacity of an inductor is limited and transient in nature. That is why an inductor is taken as a passive **element of a circuit**.

Capacitors

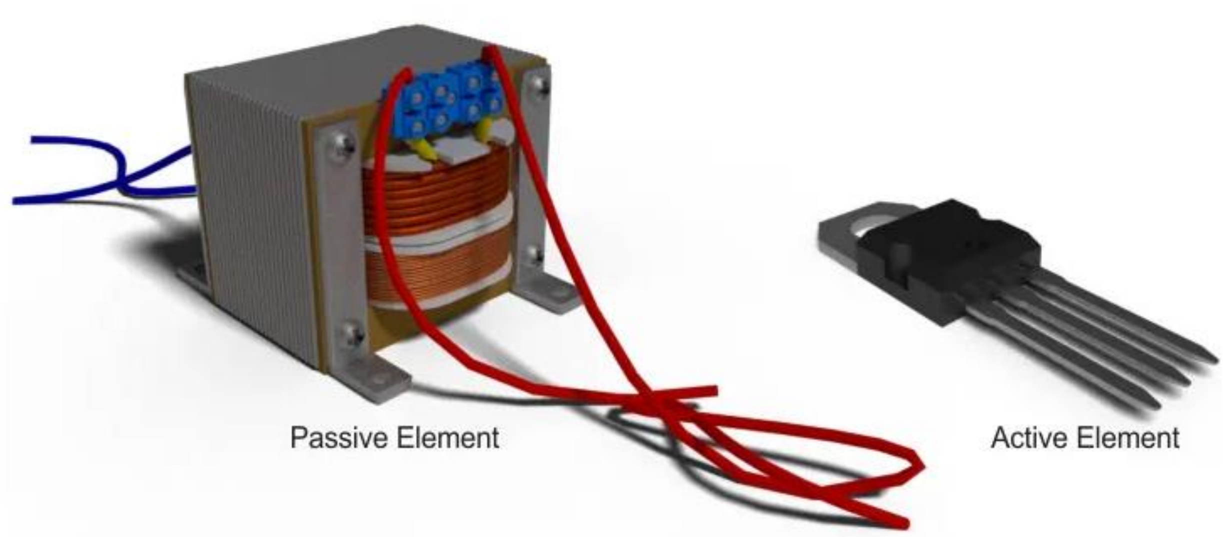
A capacitor is considered as a passive element because it can store energy in it as electric field. The energy dealing capacity of a capacitor is limited and transient – it is not actually supplying energy, it is storing it for later use.

As such it is not considered an active component since no energy is being supplied or amplified.

Transformers

A transformer is also a passive electronic component. Although this can seem surprising since transformers are often used to raise voltage levels – remember that power is kept constant.

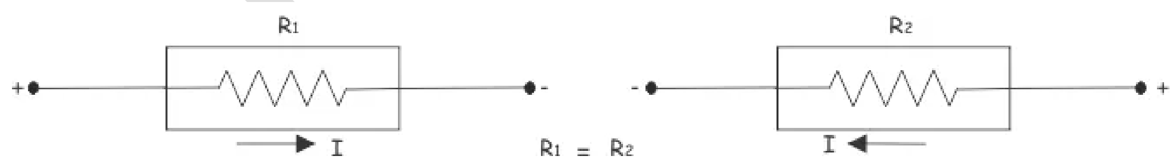
When transformers step up (or step down) voltage, power and energy remain the same on the primary and secondary side. As energy is not actually being amplified – a transformer is classified as a passive element.



Bilateral Elements

Conduction of current in both directions in a circuit element with same magnitude is termed as a **bilateral circuit element**. It offers some resistance to current flow in both directions.

Examples: Resistors, inductors, capacitors etc.

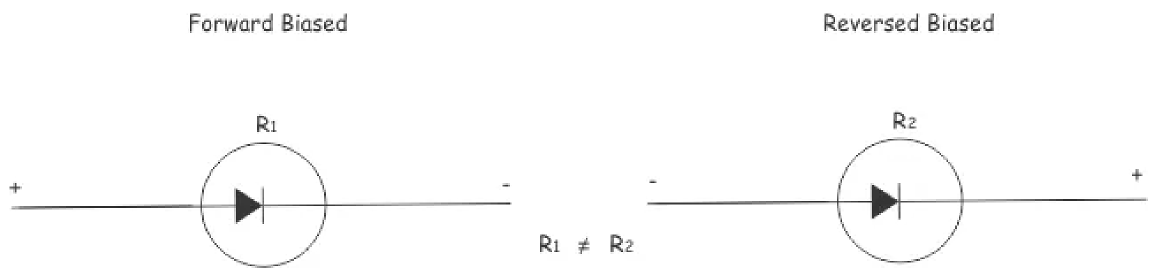


This figure shows that a bilateral circuit element can conduct from both sides and offersame resistance for current from either side.

Unilateral Elements

The **unilateral circuit element** does not offer same resistance to the current of either direction. The resistance of the **unilateral circuit element** is different for forward current than that of reverse current.

Examples: diode, transistor etc.



The figure above shows a diode as a unilateral circuit element. When diode is forward biased it offers very small resistance and conducts. While it is reverse biased, it offers very high resistance and doesn't conduct. The circuit element can be categorized in another manner, such as **lumped and distributed circuit elements**.

Lumped Elements

When the voltage across and current through the element don't vary with dimension of the element, it is called **lumped circuit elements**.

Examples: Resistor connected in any electrical circuit.

Distributed Elements

When the voltage across and current through the element change with dimensions of the element, it is called **distributed circuit element**.

Examples: Resistance of a transmission line. It varies with the length of the line.

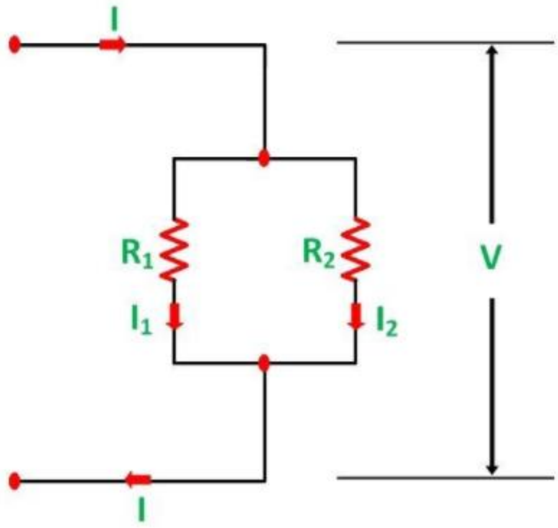
Comparison Chart of Active and Passive Elements

BASIS	ACTIVE COMPONENTS	PASSIVE COMPONENT
Nature of source	Active components deliver power or energy to the circuit.	Passive elements utilizes power or energy in the circuit.
Examples	Diodes, Transistors, SCR, Integrated circuits etc.	Resistor, Capacitor, Inductor etc.
Function of the component	Devices which produce energy in the form of voltage or current.	Devices which stores energy in the form of voltage or current.
Power Gain	They are capable of providing power gain.	They are incapable of providing power gain.
Flow of current	Active components can control the flow of current.	Passive components cannot control the flow of the current.
Requirement of external source	They require an external source for the operations.	They do not require any external source for the operations.
Nature of energy	Active components are energy donor.	Passive components are energy acceptor.

CURRENT DIVISION AND VOLTAGE DIVISION RULE

Current Division Rule

A parallel circuit acts as a current divider as the current divides in all the branches in a parallel circuit, and the voltage remains the same across them. The current division rule determines the current across the circuit impedance. The current division is explained with the help of the circuit shown below:



The current I has been divided into I_1 and I_2 into two parallel branches with the resistance R_1 and R_2 and V is the voltage drop across the resistance R_1 and R_2.

As we know,

V = IR ……..(1)

Then the equation of the current is written as:

$$I_1 = \frac{V}{R_1} \quad \text{and} \quad I_2 = \frac{V}{R_2}$$

Let the total resistance of the circuit be R and is given by the equation shown below:

$$R = \frac{R_1 R_2}{R_1 + R_2} \ldots\ldots\ldots\ldots(2)$$

Equation (1) can also be written as:

I = V/R ……….(3)

Now, putting the value of R from the equation (2) in the equation (3) we will get

$$I = \frac{V(R_1 + R_2)}{R_1 R_2} \ldots\ldots\ldots(4)$$

But

$$V = I_1R_1 = I_2R_2 \ldots\ldots\ldots\ldots..(5)$$

Putting the value of $V = I_1R_1$ from the equation (5) in equation (4), we finally get the equation as:

$$I = \frac{I_1R_1(R_1 + R_2)}{R_1R_2} = \frac{I_1}{R_2}(R_1 + R_2) \ldots\ldots..(6)$$

And now considering $V = I_2R_2$ the equation will be:

$$I = \frac{I_2R_2(R_1 + R_2)}{R_1R_2} = \frac{I_1}{R_1}(R_1 + R_2) \ldots\ldots..(7)$$

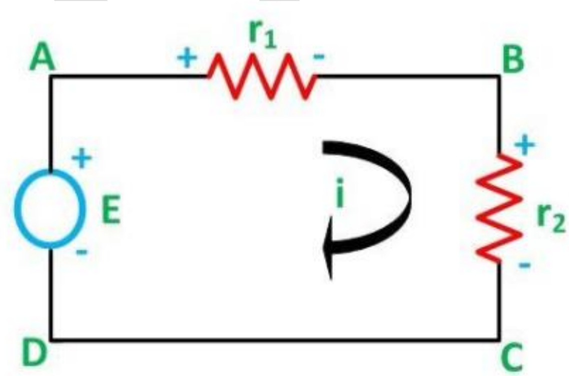
Thus, from the equation (6) and (7) the value of the current I_1 and I_2 respectively is given by the equation below:

$$I_1 = I\frac{R_2}{R_1 + R_2} \quad \text{and} \quad I_2 = I\frac{R_1}{R_1 + R_2}$$

Thus, in the current division rule, it is said that the current in any of the parallel branches is equal to the ratio of opposite branch resistance to the total resistance, multiplied by the total current.

Voltage Division Rule

The voltage division rule can be understood by considering a series circuit shown below. In a series circuit, voltage is divided, whereas the current remains the same.



Let us consider a voltage source E with the resistance r_1 and r_2 connected in series across it.

As we know,

$I = V/R$ or we can say $I = E/R$

Therefore, the current (i) in the loop ABCD will be:

$$i = \frac{E}{r_1 + r_2} \ldots\ldots\ldots (8)$$

$$\text{and} \qquad r_1 = ir_1$$

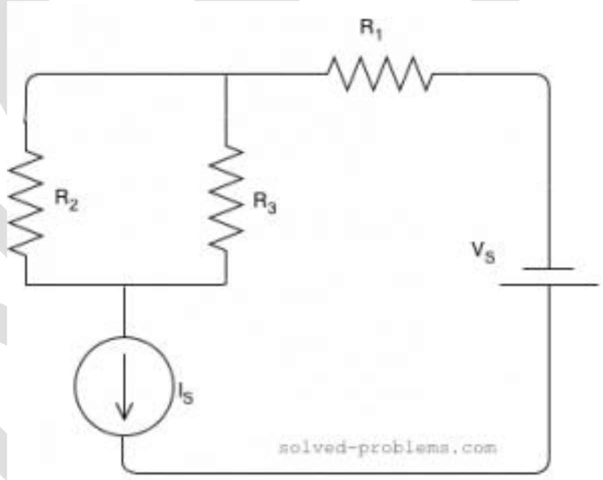
By putting the value of I from equation (8) in equation (9) the voltage across the resistance r_1 and r_2 respectively are given by the equation shown below as:

$$E_1 = \frac{Er_1}{r_1 + r_2} \text{ and } E_2 = \frac{Er_2}{r_1 + r_2}$$

Thus, the voltage across a resistor in a series circuit is equal to the value of that resistor times the total impressed voltage across the series elements divided by the total resistance of the series elements.

Example Problems

Find current of resistors, use the current division rule.



Suppose that $R_1 = 2\Omega$, $R_2 = 4\Omega$, $R_3 = 1\Omega$, $I_S = 5A$ and $V_S = 4V$

Solution:
R_2 and R_3 are parallel. The current of I_S is passing through them and it is actually divided between them. The branch with lower resistance has higher current because electrons can pass through that easier than the other branch. Using the current division rule, we get

$$I_{R_2} = \frac{R_3}{R_2+R_3} \times I_S = \frac{1}{1+4} \times 5 = 1A$$
$$I_{R_3} = \frac{R_2}{R_2+R_3} \times I_S = \frac{4}{1+4} \times 5 = 4A.$$

Note that $I_{R_2} < I_{R_3}$ because $R_2 > R_3$.

CONCEPT OF SOURCE TRANSFORMATION

Source Transformation simply means replacing one source by an equivalent source. A practical voltage source can be transformed into an equivalent practical current source and similarly a practical current source into voltage source.

Any practical voltage source or simply a voltage source consists of an ideal voltage source in series with an internal resistance or impedance (for an ideal source this impedance will be zero), the output voltage becomes independent of the load current. Cells, batteries and generators are the example of the voltage source.

For any practical current source or simply current source, there is an ideal current source in parallel with the internal resistance or impedance, for ideal current source this parallel impedance is infinity.

The semiconductor devices like transistors, etc. are treated as a current source or an output produce by the direct or alternating voltage source is called direct and alternating current source, respectively.

The voltage and current source are mutually transferable or in other words the source transformation i.e. voltage to the current source and current to a voltage source can be done. Let us understand this by considering a circuit given below:

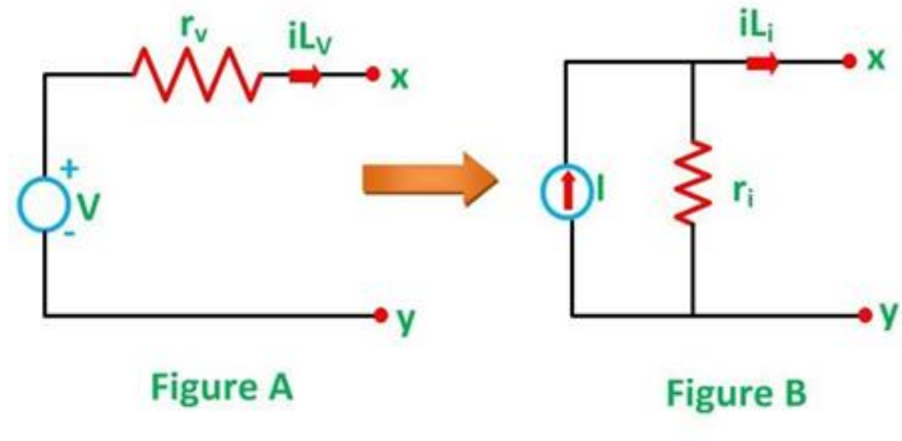


Figure A represents a practical voltage source in series with the internal resistance r_v, while figure B represents a practical current source with parallel internal resistance r_i

For the practical voltage source the load current will be given by the equation:

$$iL_v = \frac{V}{r_v + r_L} \quad \ldots\ldots\ldots (1)$$

Where,

Il_v is the load current for the practical voltage source

V is the voltage

r_v is the internal resistance of the voltage source

r_L is the load resistance

It is assumed that the load resistance r_L is connected at the terminal x-y. Similarly for the practical current source, the load current is given as:

$$iL_i = I\frac{r_i}{r_i + r_L} \quad \ldots\ldots\ldots\ldots (2)$$

Where,

Il_i is the load current for the practical current source

I is the current

r_i is the internal resistance of the current source

r_L is the load resistance connected across the terminal x-y in the figure B

Two sources become identical, when we will equate equation (1) and equation (2)

$$\frac{V}{r_v + r_L} = I \frac{r_i}{r_i + r_L}$$

However, for the current source, the terminal voltage at x-y would be Iri, x-y terminal are open. i.e.

$V = I \times r_i$

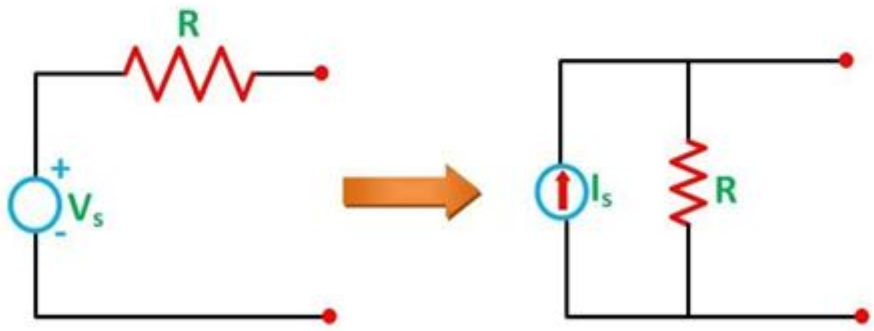
Therefore, we will get,

$$r_v + r_L = r_i + r_L \quad \text{or}$$

$$r_v = r_L$$

Therefore, for any practical voltage source, if the ideal voltage is V and internal resistance be r_v, the voltage source can be replaced by a current source I with the internal resistance in parallel with the current source.

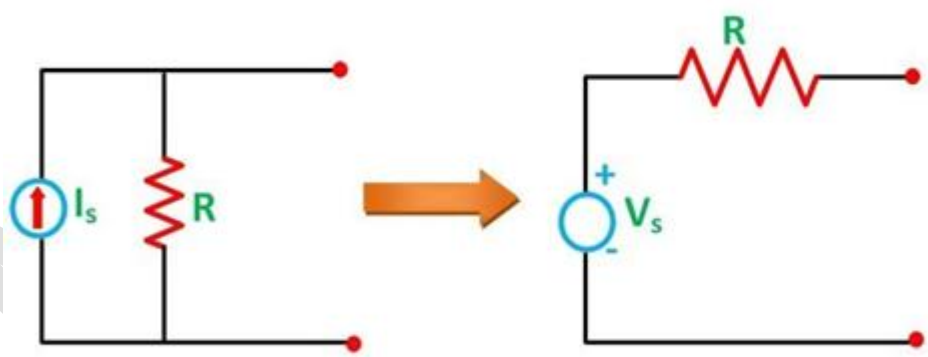
Source Transformation: Conversion of Voltage Source into Current Source



When the voltage source is connected with the resistance in series and it has to be converted into the current source than the resistance is connected in parallel with the current source as shown in the above figure.

Where $I_s = V_s /R$

Conversion of Current Source into Voltage Source



In the above circuit diagram a current source which is connected in parallel with the resistance is transformed into a voltage source by placing the resistance in series with the voltage source.

Where, $V_s = I_s / R$

Example 1:

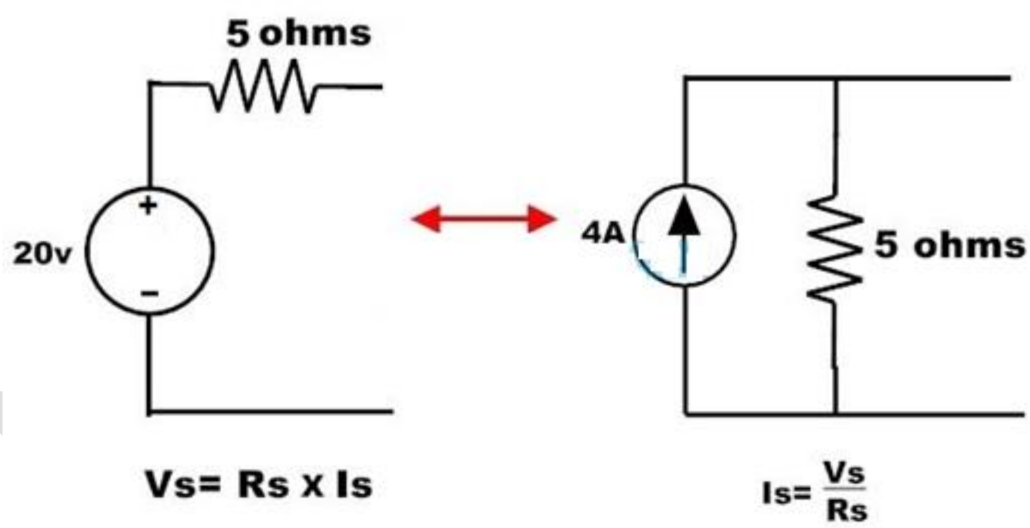
Consider the below voltage source circuit with a voltage of 20 V and a internal resistance of 5 ohms. This circuit is transformed into the current source by placing a resistor of the same value with a current source. This current source value can be determined by,

Is = Vs/Rs

= 20/ 5

= 4 amps

The equivalent current source with a current of 4A and parallel resistor of 5 ohms is shown below.



Example 2:

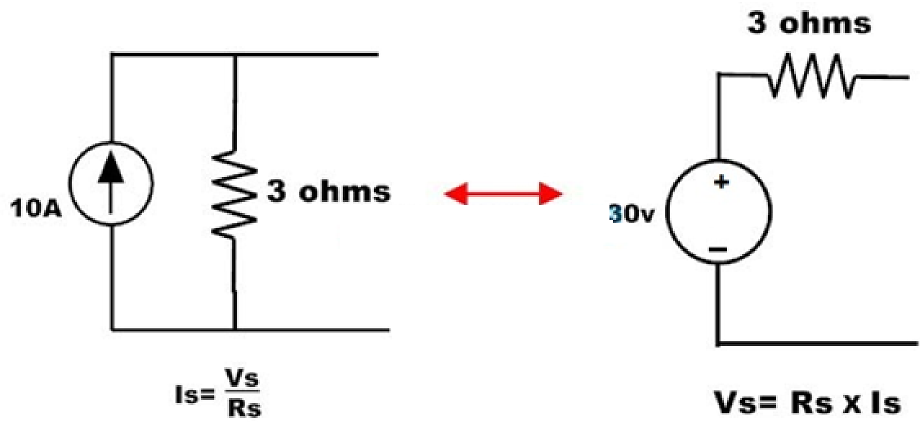
Consider the below example for current source transformation, where current source is of 10A with a parallel resistance of 3 ohms. To calculate the value of voltage in voltage source apply the simple ohms law, then,

Vs = Is * Rs

Vs = 10 * 3

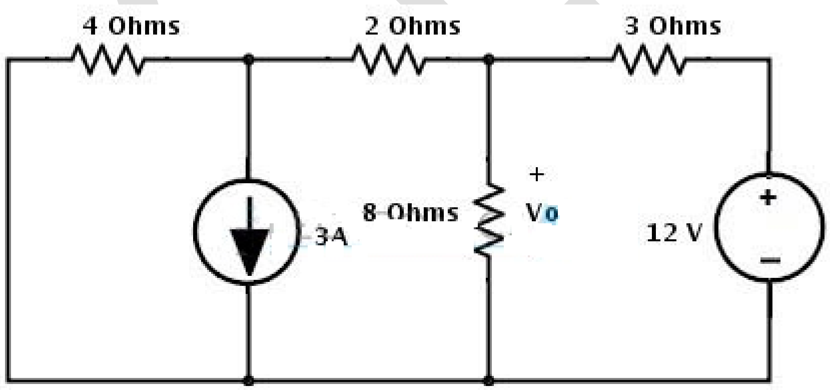
= 30 Volts.

Therefore the equivalent voltage source of this transformation consists a voltage source 30 V with a series resistance 3 ohms.

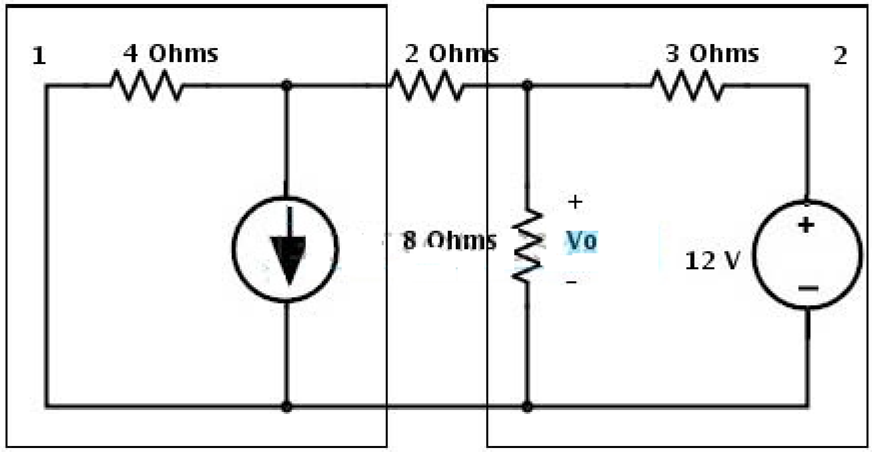


Example 3:

- Consider the below example where we have to find the voltage Vo by applying the source transformation. This circuit consists of both current and voltage sources. Let us see how we can apply source transformation to simplify the circuit below.



- In the circuit there are two areas where we can apply the source transformation since current source has a parallel resistor and voltage source has a series resistor as shown in figure. So these configurations are necessary requirements to apply the source transformation.



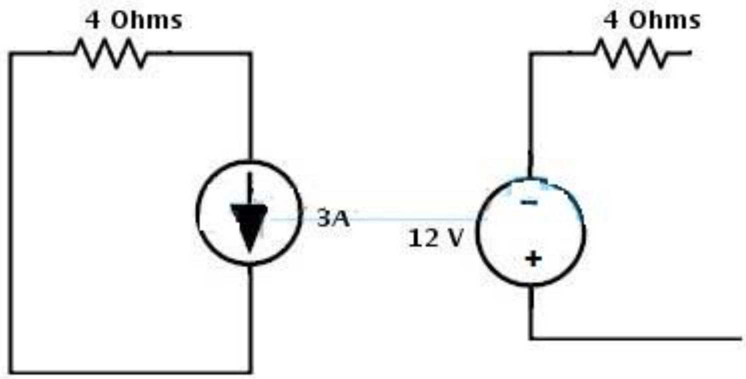
- First, consider the current source with a parallel resistance of 4 ohms. This current source can be transformed into a voltage source by 4 ohms series with a voltage source and voltage source value is determined as

Vs = Is * R

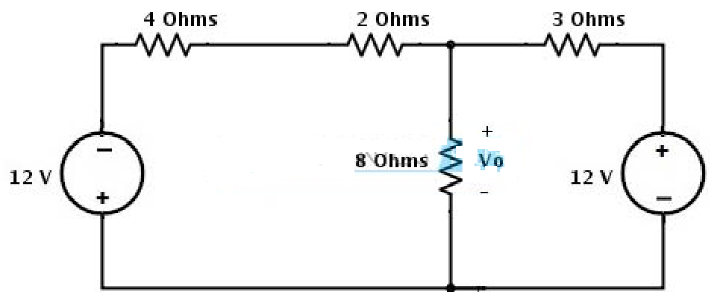
= 3* 4

= 12 Volts

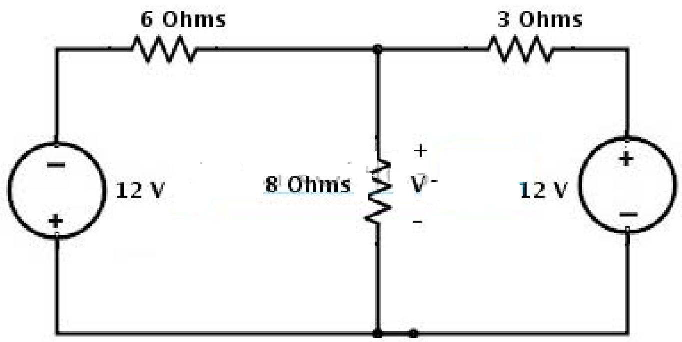
Consider the direction of the current as it downwards so the voltage terminals in voltage source are also changes as shown in figure.



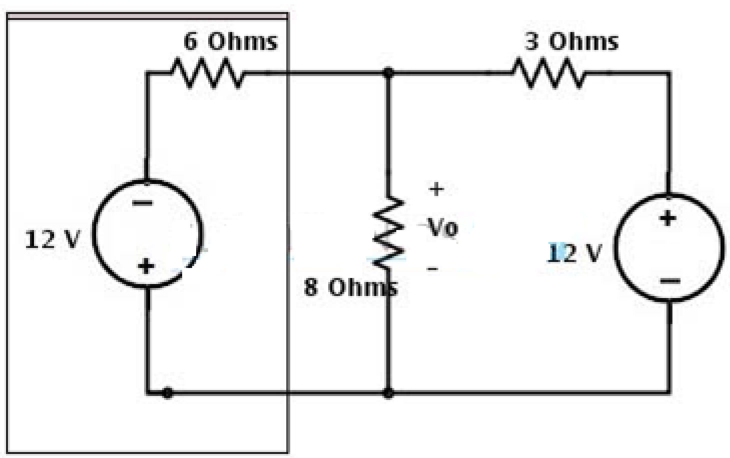
- Place the above voltage source with a series resistance in the circuit, then we get below figure.



- Resistors 4 ohms and 2 ohms are in series , hence the total series resistance will be 6 ohms as shown below.



- Again the voltage source of 12V with series resistor 6 ohms can be transformed into a current source. Therefore consider to transform it.



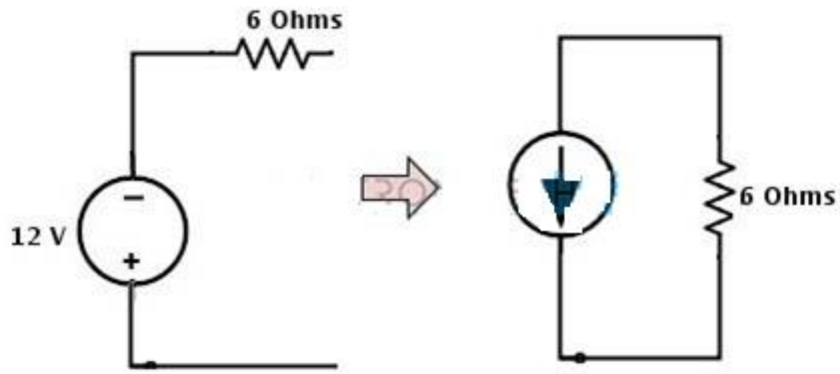
- This 12V voltage source with 6 ohm resistor combination can be converted into the current source by placing 6 ohms resistor in parallel with a current source. And the value of current in current source can be determined as

Is = Vs/R

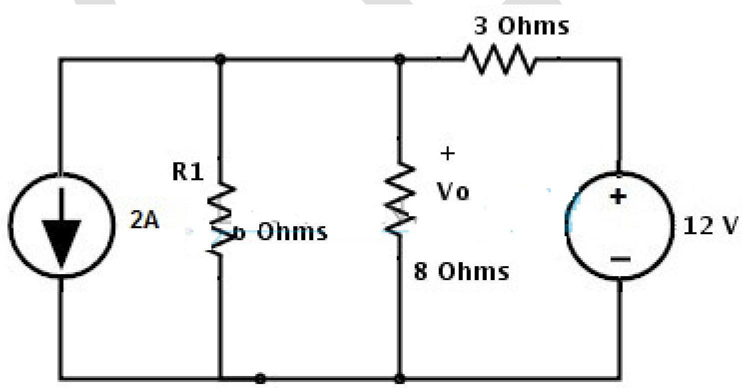
= 12/6

= 2Amps

The direction of current flow is represented in below figure.



- Insert the above current source in the main circuit, then we get



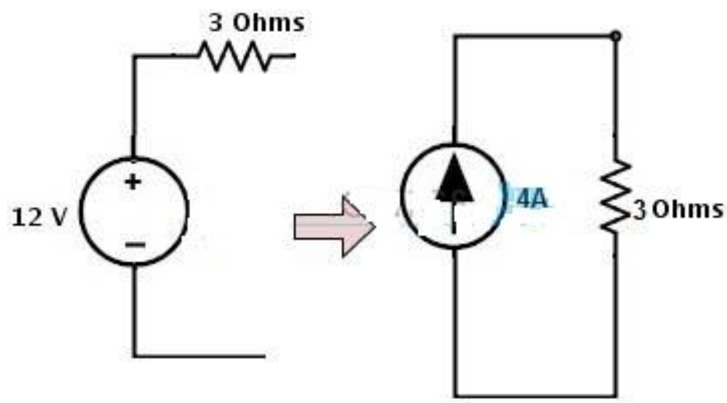
- On the right hand side, there is a voltage source with a 3 ohms resistor so this can be transformed into a current source by placing a 3 ohm resistor in parallel with a current source and this current source value is calculated as

Is = Vs/Rs

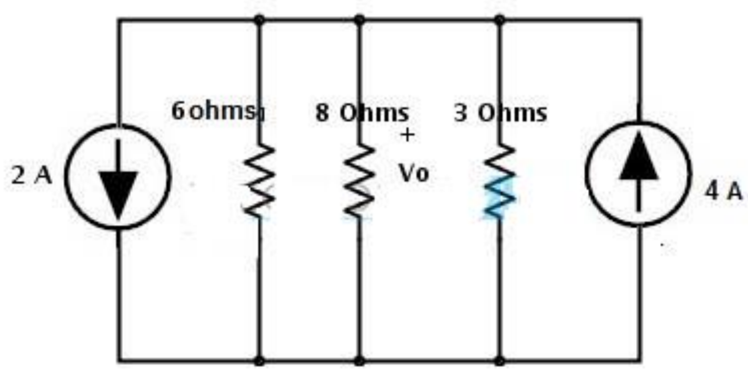
= 12/ 3

= 4 Amps

The direction of current in current source is shown in figure.



- Insert the above current source in simplified circuit, then we get a final circuit as



From the above simplified circuit the current sources are appeared to be opposite to each other. The node current through the circuit will be

Is = I1 – I2

= 4-2

= 2 amps

By applying the divider rule, the current through the resistor 8 ohms is

Io = Is * (1/Ro/ ((1/Ro) + (1/R1) + (1/R2))

= 2 * (1/8/((1/8) + (1/6) + (1/3))

= 0.4 Amps

Therefore, the voltage across the resistor 8 ohms is

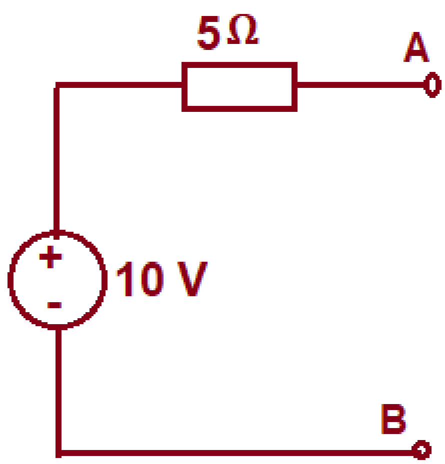
Vo = Io * Ro

= 0.4 * 8

= 3.2 Volts

Example 4:

Obtain an equivalent current source for the given voltage source:



Solution:

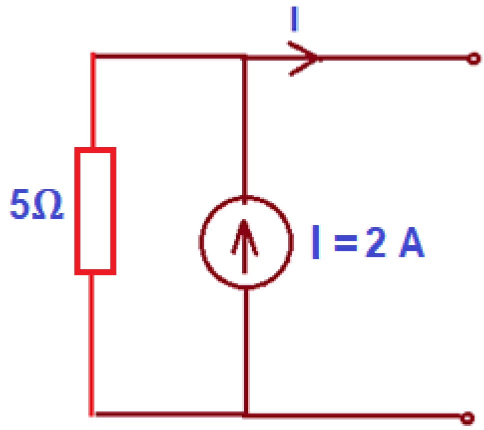
Let us first short terminals A & B and then find the current through the circuit. The current I through the circuit will be given as below.

I = V/R

= 10/5

= 2 A

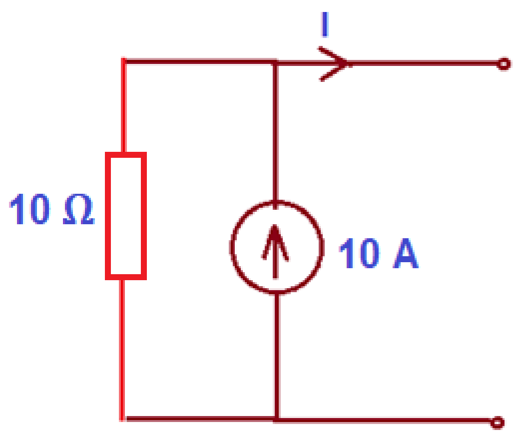
This means, the equivalent current source should be capable of supplying 2 A of current. Hence strength of source will be 2 A. Again, the internal impedance / resistance of voltage source is 5 Ω, this resistance should be connected in parallel with the current source. Therefore, the equivalent current source is given as below.



Equivalent Current Source

Example 5:

Convert the following current source to equivalent voltage source.



Solution:

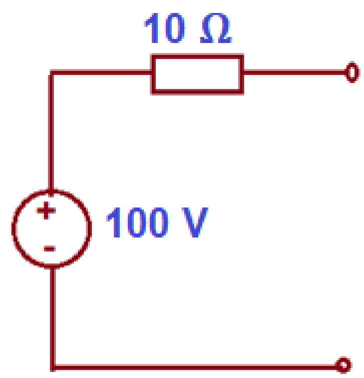
First of all, find the voltage across the terminals of the source while keeping the source terminal open. This voltage (V) is given as

V = IR

= 10×10

= 100 Volt

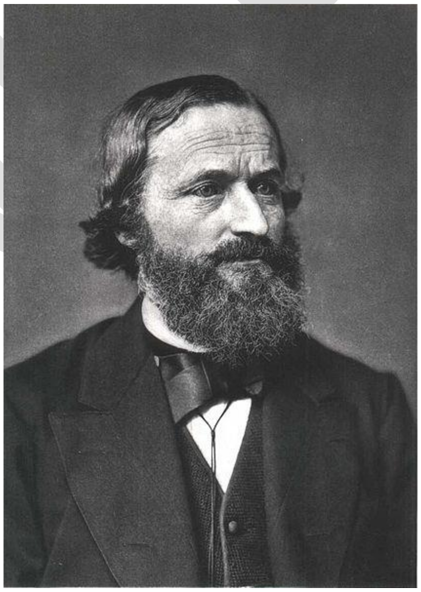
Thus, the strength of voltage source will be 100 V. The internal series resistance of this source will be equal to the resistance of current source i.e. 10 Ω. Therefore, equivalent voltage source is shown as below.



KIRCHOFF'S LAW

Kirchhoff's circuit laws lie at the heart of circuit analysis. With the help of these laws and the equation for individual components (resistor, capacitor and inductor), we have the basic tool to start analyzing circuits. In this article, we will discuss Kirchhoff's current and voltage law and how to employ them in circuit analysis.

History about Gustav Robert Kirchhoff



Gustav Robert Kirchhoff(1824-1887)

Gustav Robert Kirchhoff, a German physicist, was born on March 12, 1824, in Konigsberg, Prussia. His first research topic was on the conduction of electricity. This research led to Kirchhoff formulating the Laws of Closed Electric Circuits in 1845. These laws were eventually named after Kirchhoff and are now known as Kirchhoff's Voltage and Current Laws. Since these laws apply to all electric circuits, understanding their fundamentals is paramount in the understanding of how an electronic circuit functions. Although these laws have 56abeled56ized Kirchhoff in the field of Electrical Engineering, he has additional discoveries. He was the first person to verify hat an electrical impulse travelled at the speed of light. Furthermore, Kirchhoff made a major contribution to the study of spectroscopy and he advanced the research into blackbody radiation.

Many of the electrical circuits are complex in nature and the computations required to find the unknown quantities in such circuits, using simple ohm's law and series/parallel combination simplifying methods is not possible. Therefore, in order to simplify these circuits Kirchhoff's laws are used.

These laws are the fundamental analytical tools that are used to find the solutions of voltages and currents in an electric circuit whether it can be AC or DC. Elements in an electric circuit are connected in numerous possible ways, thus to find the parameters in an electrical circuit these laws are very helpful.

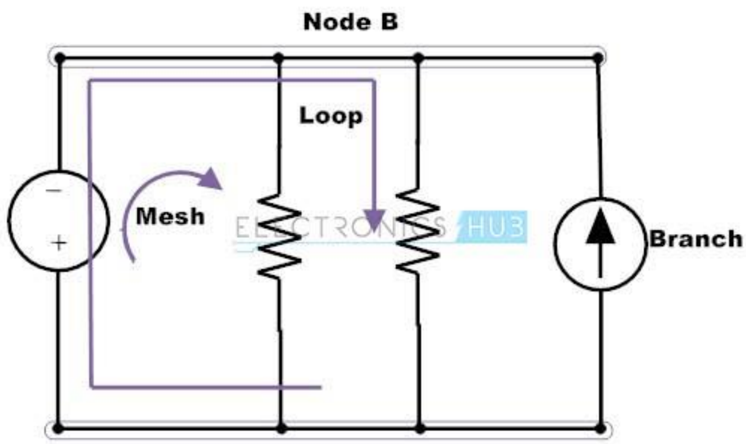
Before going to know more about Kirchhoff's law, we have to consider some of the terms related to electric circuits.

Node: Node or junction is a point in the circuit where two or more electrical elements are connected. This specifies a voltage level with a reference node in a circuit.

Branch: The continuous conducting path between two junctions which contains electrical element in a circuit is referred as branch.

Loop: In an electrical circuit a loop is an independent closed path in a circuit that follows the sequence of branches in such a way that it must start and ends with same node and it shouldn't touch any other junction or node more than once.

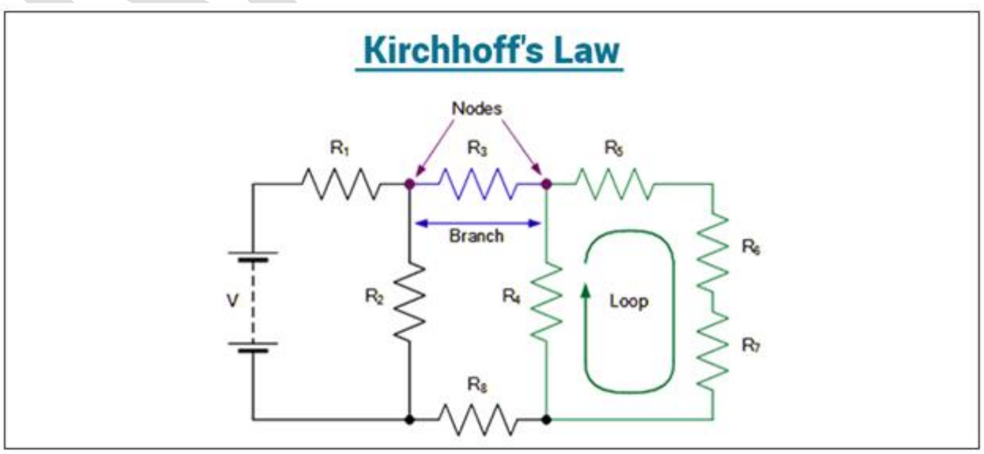
Mesh: In an electrical circuit mesh is a loop that doesn't contain any other loop in its interior.



What are Kirchhoff's Law?

In 1845, a German physicist, Gustav Kirchhoff developed a pair of laws that deal with the conservation of current and energy within electrical circuits. These two laws are commonly known as Kirchhoff's Voltage and Current Law. These laws help in calculating the electrical resistance of a complex network or impedance in case of AC and the current flow in different streams of the network. In the next section, let us look at what these laws state.

Kirchhoff's laws are a set of laws that quantify how current flows through a circuit and how voltage varies around a loop in a circuit. They are used to govern the conservation of charge and energy in standard electrical circuits. Two significant circuital laws are applied in every simple and complex electrical circuit in physics. These laws were postulated in 1845 by German physicist Gustav Kirchhoff. The proof of Kirchhoff's law can be obtained by using Maxwell's equations.



What do Kirchhoff's laws state?

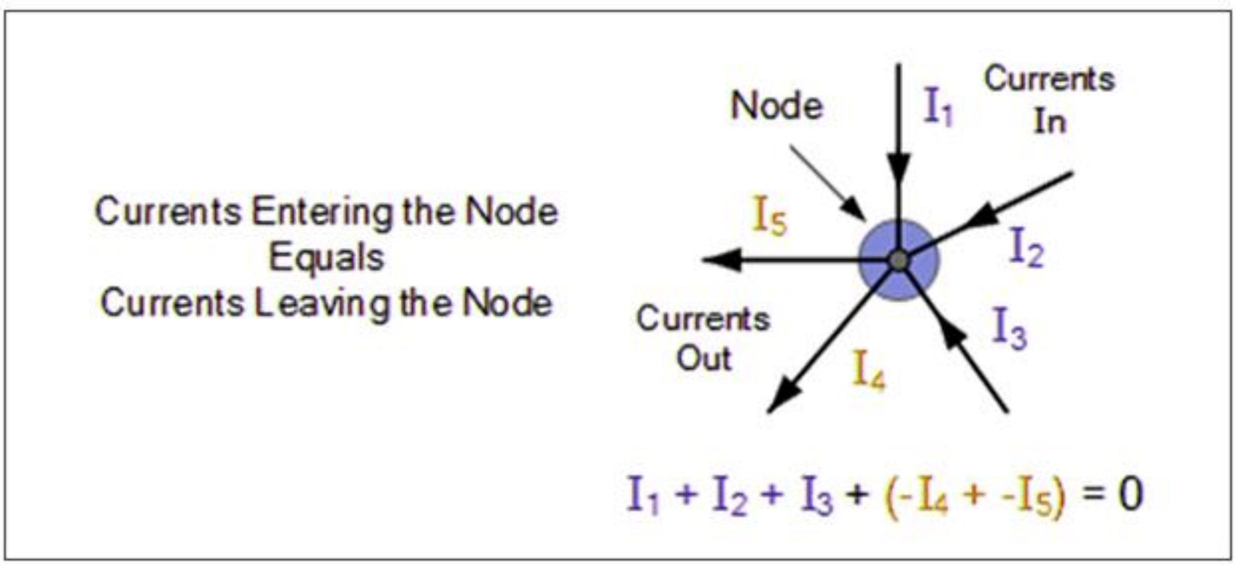
- Kirchhoff's Current Law goes by several names as Kirchhoff's First Law and Kirchhoff's Junction Rule. According to the Junction rule, in a circuit, the total of the currents in a junction is equal to the sum of currents outside the junction.
- Kirchhoff's Voltage Law goes by several names as Kirchhoff's Second Law and Kirchhoff's Loop Rule. According to the loop rule, the sum of the voltages around the closed loop is equal to null.

Kirchhoff's First Law

According to Kirchhoff's Current Law,

The total current entering a junction or a node is equal to the charge leaving the node as no charge is lost.

Put differently, the algebraic sum of every current entering and leaving the node has to be null. This property of Kirchhoff law is commonly called as Conservation of charge wherein, I(exit) + I(enter) = 0.



In the above figure, the currents I_1, I_2 and I_3 entering the node is considered positive, likewise, the currents I_4 and I_5 exiting the nodes is considered negative in values. This can be expressed in the form of an equation:

I1 + I2 + I3 – I4 – I5 = 0

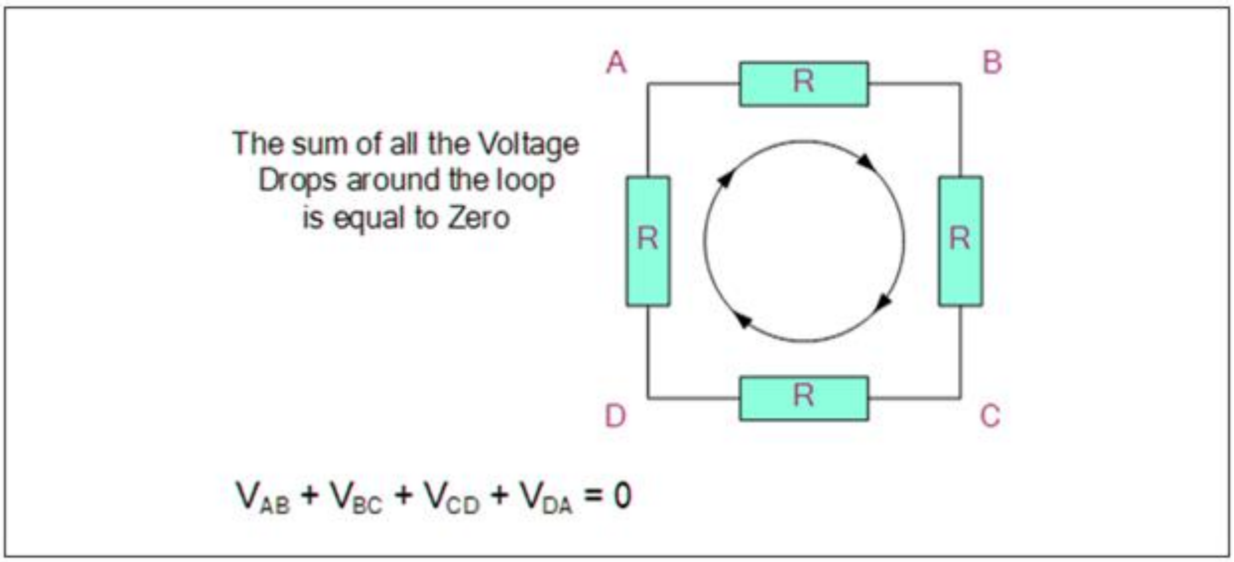
The term Node refers to a junction or a connection of two or more current-carrying routes like cables and other components. Kirchhoff's current law can also be applied to analyze parallel circuits.

Kirchhoff's Second Law

According to Kirchhoff's Voltage Law,

The voltage around a loop equals to the sum of every voltage drop in the same loop for any closed network and also equals to zero.

Put differently, the algebraic sum of every voltage in the loop has to be equal to zero and this property of Kirchhoff's law is called as conservation of energy.



When you begin at any point of the loop and continue in the same direction, note the voltage drops in all the direction either negative or positive and return to the same point. It is essential to maintain the direction either counterclockwise or clockwise; else the final voltage value will not be equal to zero. The voltage law can also be applied in analyzing circuits in series.

When either AC circuits or DC circuits are analysed based on Kirchhoff's circuit laws, you need to be clear with all the terminologies and definitions that describe the circuit components like paths, nodes, meshes, and loops.

Differences Between Kirchhoff's Current and Voltage Laws

Kirchhoff's Current Law vs. Kirchhoff's Voltage Law	
KCL	KVL
States that the sum of all the currents entering a particular node is equal to the sum of all currents leaving the node	States that the sum of all the voltages around a closed path (loop) is zero
Nodal analysis is preferred to obtain node potentials as the currents entering/leaving the node can be expressed in terms of node potential	Loop analysis is preferred to obtain loop currents as loop potential differences can be expressed in terms of loop currents

Kirchhoff's Law Circuit Diagram

A circuit diagram consists of a source of current and voltage along with resistances and impedances, which can be in series, or parallel, or combination of the two. The polarity of the source is indicated by positive and negative signs, which automatically applies to the resistances.

Resistances in Series

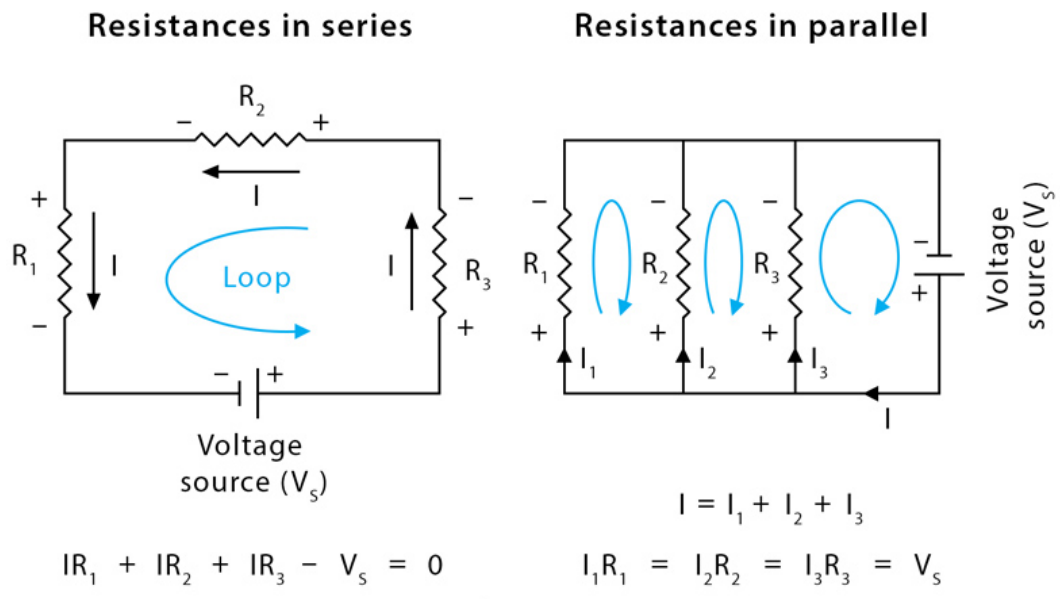
Resistances are said to be in series when they are connected in a single path. The current from a source flows through all the resistances in a closed loop.

Resistances in Parallel

Resistances are said to be in parallel when the path branches and each branch consists of one resistance. The current from the source splits into different paths. The equation for replacing resistances in parallel is a bit more complicated.

Sign Convention

The sign convention for applying signs to the voltage polarities in KVL equations is as follows. When traversing the loop, if the positive terminal of a voltage difference is encountered before the negative terminal, the voltage difference will be interpreted as positive. If the negative terminal is encountered first, the voltage difference will be interpreted as negative.



Applications of Kirchhoff's Law

Kirchhoff's laws are applicable to analyze any circuit regardless of the composition and structure of it. Some of its applications include

- To find the unknown resistances, impedances, voltages, and currents (direction as well as value).
- In a branched circuit, currents passing each branch are determined by applying KCL at every junction and KVL in every loop.
- In a looped circuit, the current passing each independent loop is determined by applying KVL for each loop and calculating the currents in any resistance of the circuit.

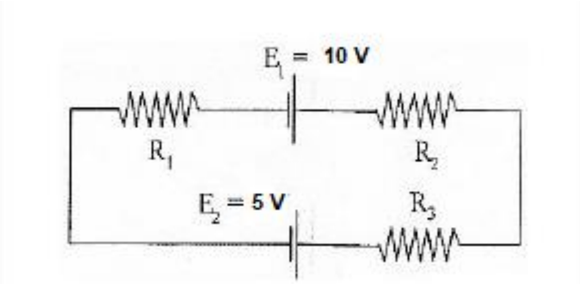
Limitations of Kirchhoff's Law

Kirchhoff's laws are limited in their applicability. They are valid for all cases in which total electric charge is constant in the region into consideration. Essentially, this is always true, so long as the law is applied for a specific point. Over a region, however, charge density may not be constant. Because the charge is conserved, the only way this is possible is if there is a flow of charge across the boundary of the region. This flow would result in current, thus violating Kirchhoff's laws.

Another limitation is that it works under the assumption that there is no fluctuating magnetic field in the closed-loop. Electric fields and emf could be induced, which causes Kirchhoff's laws to break in the presence of a variable magnetic field.

Kirchhoff's Law Solved Example

If R1 = 2Ω, R2 = 4Ω, R3 = 6Ω, determine the electric current that flows in the circuit below.



Solution:

Following are the things that you should keep in mind while approaching the problem:

Following are the things that you should keep in mind while approaching the problem:

You need to choose the direction of the current. In this problem, let us choose the clockwise direction.

When the current flows across the resistor, there is a potential decrease. Hence, V = IR is signed negative.

If the current moves from low to high then the source of emf I signed positive because of the charging of energy at the emf source. Likewise, if the current moves from high to low voltage (+ to -) then the source of emf I signed negative because of the emptying of energy at the emf source.

In this solution, the direction of the current is the same as the direction of clockwise rotation.

– IR1 + E1 – IR2 – IR3 – E2 = 0

Substituting the values in the equation, we get

–2I + 10 – 4I – 6I – 5 = 0

-12I + 5 = 0

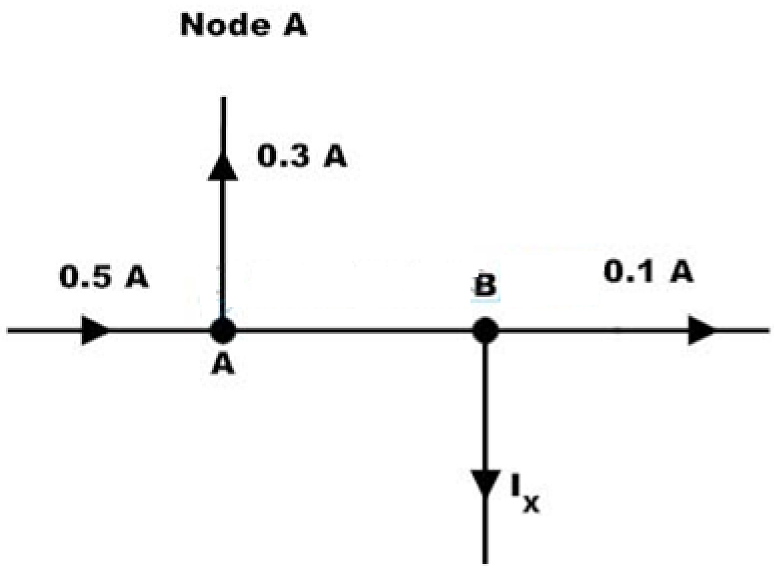
I = -5/-12

I = 0.416 A

The electric current that flows in the circuit is 0.416 A. The electric current is signed positive which means that the direction of the electric current is the same as the direction of clockwise rotation. If the electric current is negative then the direction of the current would be in anti-clockwise direction.

Example Problem of KCL

Consider the below figure where we have to determine the currents IAB and Ix by using KCL .



By applying Kirchhoff's Current Law at point A, we get

IAB = 0.5 – 0.3

IAB = 0.2 Amps

Similarly by applying KCL at point B, we get

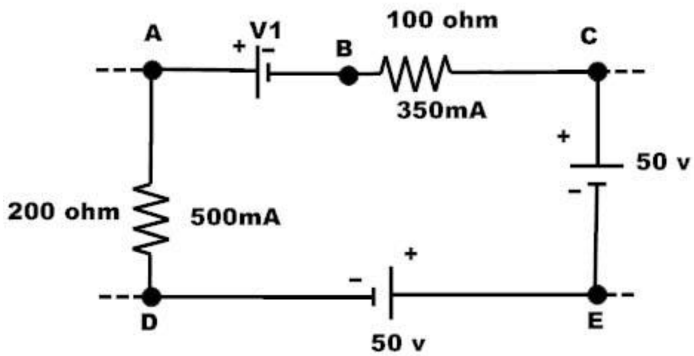
IAB = 0.1 + Ix

0.2 = 0.1 + Ix

Ix = 0.2 – 0.1 = 0.1 Amps

Kirchhoff's Voltage Law Example

1. Let us consider the single loop circuit which is shown below and assume the current flow direction as DEABCD closed path. In this circuit, by using KVL we have to find the voltage V1.



By applying KVL to this closed loop, we can write as

VED + VAE + VBA + VCB + VDC = 0

Where

Voltage of point E with respect to point D, VED = -50 V

Voltage of point D with respect to point C, VDC = -50 V

Voltage of point A with respect to point E. VAE = I * R

VAE = 500m* 200

VAE = 100 V

Similarly Voltage at point C with respect to pint B, VCB = 350m*100

VCB = 35V

Consider voltage at point A with respect to point B, VAB = V1

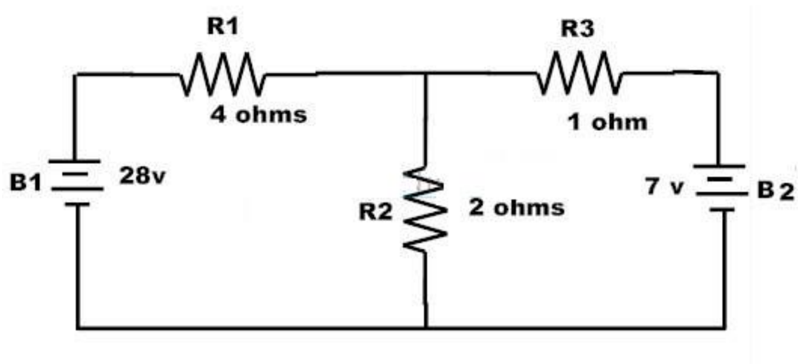
VBA= -V1

Then by using KVL

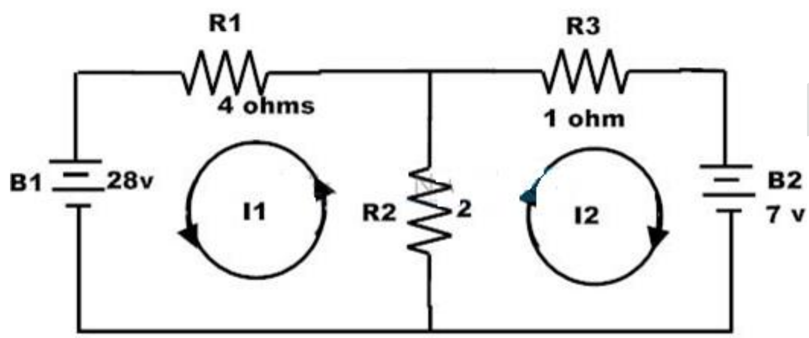
-50 + 100 – V1 + 35 – 50 = 0

V1 = 35 Volts

2. Consider the below typical two loop circuit where we have to find the currents I1 and I2 by applying the Kirchhoff's laws.



There are two loops inside the circuit and consider the loop paths as shown in figure.



By applying KVL to these loops we get

For first loop,

$2 (I1 + I2) + 4I1 – 28 = 0$

$6I1 + 2I2 = 28$ ——— (1)

For second loop,

$-2(I1 + I2) – 1I2 + 7 = 0$
$-2I1 – 3I2 = -7$ ——— (2)

By solving the above 1 and 2 equations we get,

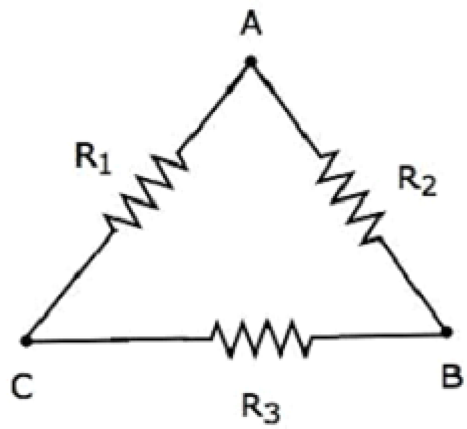
$I1 = 5A$ and $I2 = -1$ A

STAR-DELTA TRANSFORMATIONS

For example, the resistors connected in either delta (δ) form or star form. In such situations, we have to **convert** the network of one form to the other in order to simplify it further by using series combination or parallel combination. In this chapter, let us discuss about the **Delta to Star Conversion**.

DELTA NETWORK

Consider the following **delta network** as shown in the following figure.



The following equations represent the **equivalent resistance** between two terminals of delta network, when the third terminal is kept open.

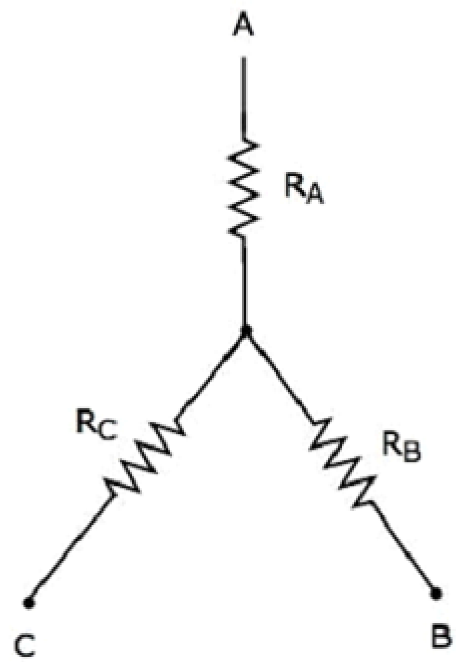
$$R_{AB} = \frac{(R_1 + R_3)R_2}{R_1 + R_2 + R_3}$$

$$R_{BC} = \frac{(R_1 + R_2)R_3}{R_1 + R_2 + R_3}$$

$$R_{CA} = \frac{(R_2 + R_3)R_1}{R_1 + R_2 + R_3}$$

STAR NETWORK

The following figure shows the **equivalent star network** corresponding to the above delta network.



The following equations represent the **equivalent resistance** between two terminals of star network, when the third terminal is kept open.

$$R_{AB} = R_A + R_B$$

$$R_{BC} = R_B + R_C$$

$$R_{CA} = R_C + R_A$$

STAR NETWORK RESISTANCES IN TERMS OF DELTA NETWORK RESISTANCES

We will get the following equations by equating the right-hand side terms of the above equations for which the left-hand side terms are same.

$$R_A + R_B = \frac{(R_1+R_3)R_2}{R_1+R_2+R_3} \quad \text{Equation 1}$$

$$R_B + R_C = \frac{(R_1+R_2)R_3}{R_1+R_2+R_3} \quad \text{Equation 2}$$

$$R_C + R_A = \frac{(R_2+R_3)R_1}{R_1+R_2+R_3} \quad \text{Equation 3}$$

By adding the above three equations, we will get

$$2(R_A + R_B + R_C) = \frac{2(R_1R_2 + R_2R_3 + R_3R_1)}{R_1 + R_2 + R_3}$$

$$\Rightarrow R_A + R_B + R_C = \frac{R_1R_2+R_2R_3+R_3R_1}{R_1+R_2+R_3} \quad \text{Equation 4}$$

Subtract Equation 2 from Equation 4.

$$R_A + R_B + R_C - (R_B + R_C) = \frac{R_1R_2+R_2R_3+R_3R_1}{R_1+R_2+R_3} - \frac{(R_1+R_2)R_3}{R_1+R_2+R_3}$$

$$R_A = \frac{R_1R_2}{R_1 + R_2 + R_3}$$

By subtracting Equation 3 from Equation 4, we will get

$$R_B = \frac{R_2R_3}{R_1 + R_2 + R_3}$$

By subtracting Equation 1 from Equation 4, we will get

$$R_C = \frac{R_3R_1}{R_1 + R_2 + R_3}$$

By using the above relations, we can find the resistances of star network from the resistances of delta network. In this way, we can convert a **delta network** into a **star network**.

DELTA NETWORK RESISTANCES IN TERMS OF STAR NETWORK RESISTANCES

Let us manipulate the above equations in order to get the resistances of delta network in terms of resistances of star network.

- **Multiply** each set of two equations and then **add**.

$$R_AR_B + R_BR_C + R_CR_A = \frac{R_1R_2^2R_3 + R_2R_3^2R_1 + R_3R_1^2R_2}{(R_1 + R_2 + R_3)^2}$$

$$\Rightarrow R_AR_B + R_BR_C + R_CR_A = \frac{R_1R_2R_3(R_1 + R_2 + R_3)}{(R_1 + R_2 + R_3)^2}$$

$$\Rightarrow R_AR_B + R_BR_C + R_CR_A = \frac{R_1R_2R_3}{R_1+R_2+R_3} \quad \text{Equation 4}$$

- By dividing Equation 4 with Equation 2, we will get

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

$$\Rightarrow R_1 = R_C + R_A + \frac{R_C R_A}{R_B}$$

- By dividing Equation 4 with Equation 3, we will get

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

- By dividing Equation 4 with Equation 1, we will get

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

By using the above relations, we can find the resistances of delta network from the resistances of star network. In this way, we can convert **star network into delta network**.

Solved Examples on Star/Delta Transformation

Q1). Determine the resistance between the terminals A&B and hence find the current through the voltage source. Refer figure

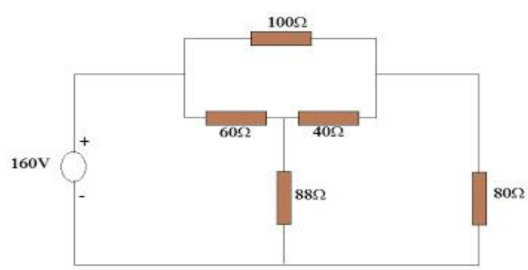


Figure 16.1

Answer:

See figure

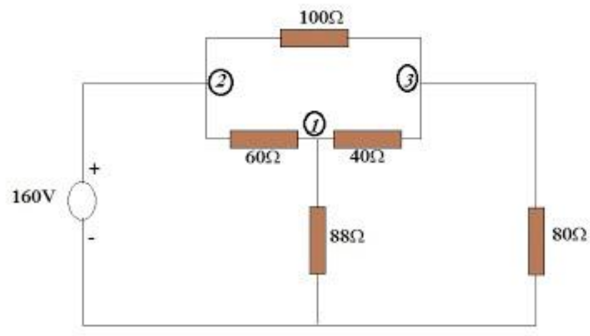


Figure 16.1 (a)

The resistors in between point 1, 2&3 are about to replace by a star connected system. Otherwise is difficult to find the total resistance.

So we have to use the delta to star transformation equations.

$\boldsymbol{R_1 = R_{12}R_{31} / (R_{12}+R_{23}+R_{31})}$

R_1 = (60*40)/ (60+40+100)

$R_1 = 12\Omega$

$\boldsymbol{R_2 = R_{23}R_{12} / (R_{12}+R_{23}+R_{31})}$

R_1 = (100*60)/ 200

$R_1 = 30\Omega$

$\boldsymbol{R_3 = R_{31}R_{23} / (R_{12}+R_{23}+R_{31})}$

R_3 = (100*40)/ 200

$R_3 = 20\Omega$

So we can redraw the network as shown in figure

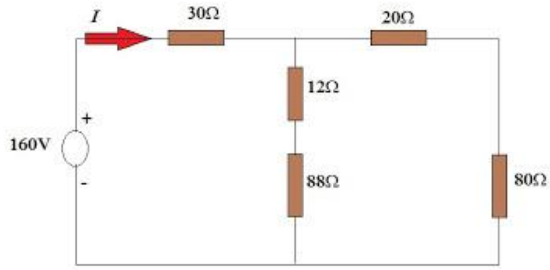


Figure 16.2

Now we can easily find the total resistance between A&B terminals

R_{total} = [(80+20)//(88+12)] + 30

R_{total} = 50 + 30

R_{total} = 80Ω

Applying ohm's law to the total resistance,

I = V/R

I = 160v/80Ω

I = 2A

Q2) Find the total resistance between A&B terminals for the network shown in figure 16.3

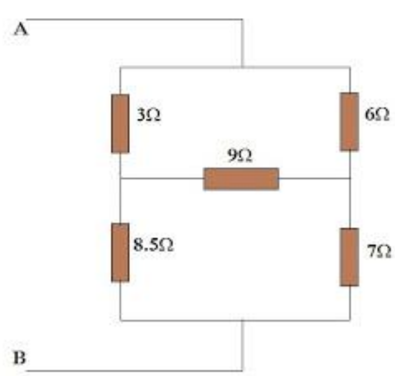


Figure 16.3

Answer:

See figure

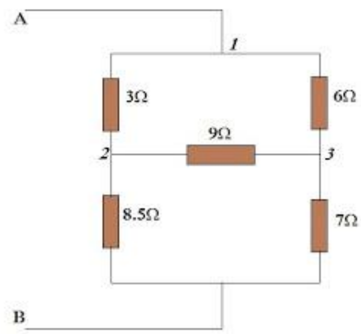


Figure 16.3(a)

We are about to replace the delta system by star system in between point 1, 2 &3

So we have to use the delta to star transformation equations.

$\boldsymbol{R_1 = R_{12}R_{31} / (R_{12}+R_{23}+R_{31})}$

$R_1 = (3*6)/ (3+6+9)$

$\mathbf{R_1 = 1\Omega}$

$\boldsymbol{R_2 = R_{23}R_{12} / (R_{12}+R_{23}+R_{31})}$

$R_2 = (9*3)/18$

$\mathbf{R_2 = 1.5\Omega}$

$\boldsymbol{R_3 = R_{31}R_{23} / (R_{12}+R_{23}+R_{31})}$

$R_3 = (6*9)/18$

$\mathbf{R_3 = 3\Omega}$

So now we can replace the system as shown in figure

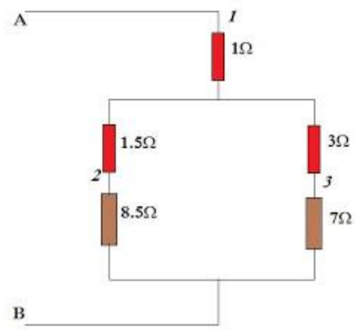


Figure 16.4

Now we can easily find the total resistance between A&B terminals

R_{AB} = (7Ω+3Ω) + (8.5Ω+1.5Ω) + 1Ω

R_{AB} = 6Ω

Q3). Find the total resistance between A&B terminals (R_{AB}) shown in figure

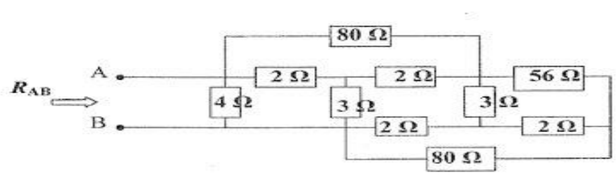


Figure 16.5

Answer:

You must understand that you have to use star/delta transformation for this problem. Unlike other problems, in this case it is not pointed out which system of resistance you must replace. So you yourself have to point it out.

This is very important. Though the tutorial problems guide you to find the replaceable systems, in practical level you will have to guide yourself manually. This means you must know how to choose the correct system to apply delta/star transformation.

See figure

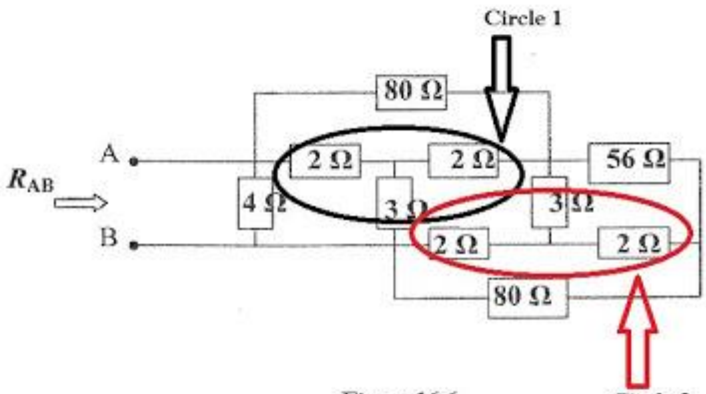


Figure 16.6

See the circled systems in the figure. You have to replace these systems with delta systems. If you see it carefully, you'll see that both systems are same (one is upside down of the other). So you don't need to find two different sets of delta systems. See figure 16.7

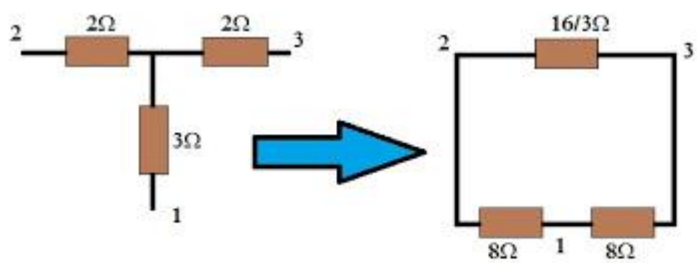


Figure 16.7

This figure shows you the star to delta transformation. As the required equation for transformation are given in my previous post, I've directly put the values for the delta system shown in the above figure. Steps for this calculation are shown below.

$\boldsymbol{R_{12} = R_1 + R_2 + (R_1R_2/R_3)}$

$R_{12} = 3 + 2 + (3*2)/2$

$\mathbf{R_{12} = 8\Omega}$

$\boldsymbol{R_{23} = R_2 + R_3 + (R_2R_3/R_1)}$

$R_{23} = 2 + 2 + (2*2)/3$

$\mathbf{R_{23} = 16/3\Omega}$

$\boldsymbol{R_{31} = R_3 + R1 + (R_3R_1/R_2)}$

$R_{13} = 3 + 2 + (3*2)/2$

$\mathbf{R_{13} = 8\Omega}$

So we can redraw the network as shown in figure 16.8

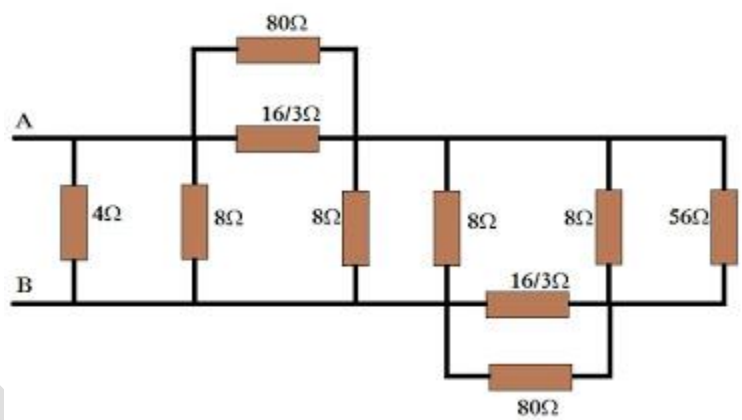


Figure 16.8

Now we can easily find the total resistance between A&B terminals. For your better understanding I've simplified the network. See figure

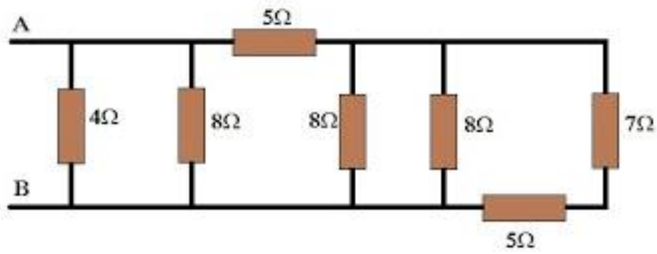


Figure 16.9

So now it is simple.

R_{AB} = { [(7+5)//8//8] + 5 } //8//4

R_{AB} = (3 + 5) // 8 // 4

R_{AB} = 4//4

$R_{AB} = 2\Omega$

MESH ANALYSIS/MESH CURRENT METHOD

In circuit analysis, simple circuits can be analyzed by using the basic analyzing tools like ohms law, KVL and KCL. But for a complex circuit that consists of various controlled sources, these tools in addition with series and parallel methods are unreliable. Therefore, to find the variables of a branch in such circuit, nodal and mesh (or loop) analysis methods are used. By using these classical methods, circuit variables like voltage and currents are easily determined in any branch without a great difficulty. Let us see in detail about mesh analysis.

Mesh Analysis

Mesh is a loop that doesn't consists of any other loop inside it. Mesh analysis technique, uses mesh currents as variables , instead of currents in the elements to analyse the circuit. Therefore, this method absolutely reduces the number of equations to be solved . Mesh analysis applies the Kirchhoff's Voltage Law (KVL) to determine the unknown currents in a given circuit. Mesh analysis is also called as mesh-current method or loop analysis. After finding the mesh currents using KVL, voltages anywhere in a given circuit can be determined by using

Ohms law.

Steps to Analyse the mesh analysis technique

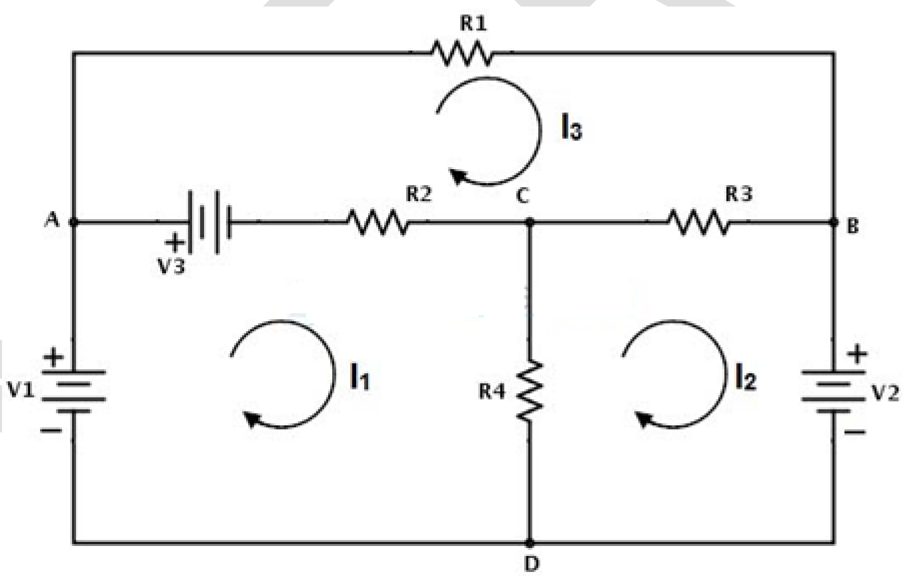
1) Check whether there is a possibility to transform all current sources in the given circuit to voltage sources.

2) Assign the current directions to each mesh in a given circuit and follow the same direction for each mesh.

3) Apply KVL to each mesh and simplify the KVL equations.

4) Solve the simultaneous equations of various meshes to get the mesh currents and these equations are exactly equal to the number of meshes present in the network.

Consider the below DC circuit to apply the mesh current analysis, such that currents in different meshes can be found. In the below figure there are three meshes present as ACDA, CBDC and ABCA but the path ABDA is not a mesh. As a first step, the current through each mesh is assigned with the same direction as shown in figure.



Secondly, for each mesh we have to apply KVL. By applying KVL around the first loop or mesh we get

V1 – V3 – R2 (I1 – I 3) – R4 (I1 – I 2) = 0

V1 – V3 = I1 (R2 + R4) – I2R4 – I3R2 ………………(1)

Similarly , by applying KVL around second mesh we get,

$-V2 - R3 (I 2 - I 3) - R4 (I 2 - I1) = 0$

$- V2 = - I1R4 + I 2 (R3 + R4) - I 3 R3$ ……………………….(2)

And by applying KVL around third mesh or loop we get,

$V3 - R1I 3 - R3(I 3 - I 2) - R2(I 3 - I1) = 0$

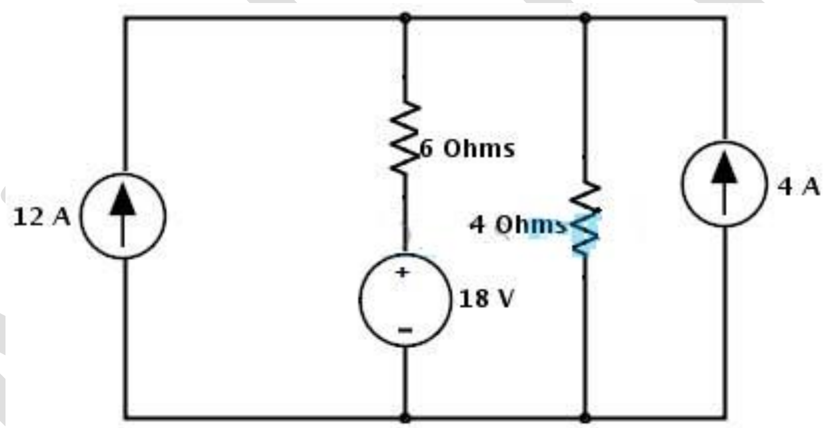
$V3 = - I1R2 - I2R3 + I3(R1 + R2 + R3)$ ……………………….(3)

Therefore, by solving the above three equations we can obtain the mesh currents for each mesh in the given circuit.

Example problems on mesh analysis:

Example 1:

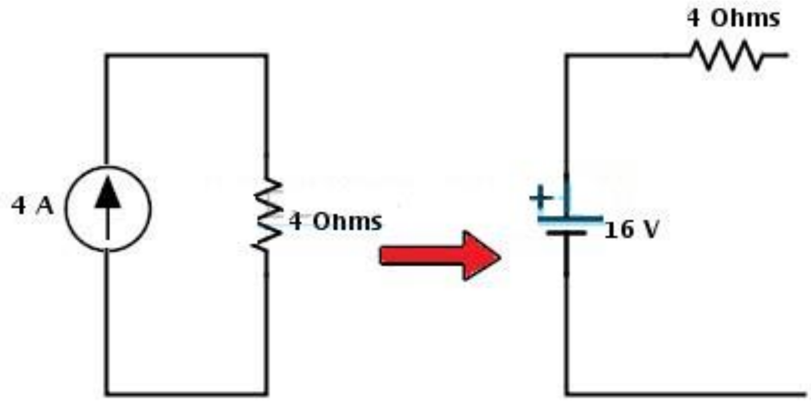
Consider the below example in which we find the voltage across the 12A current source using mesh analysis. In the given circuit all the sources are current sources.



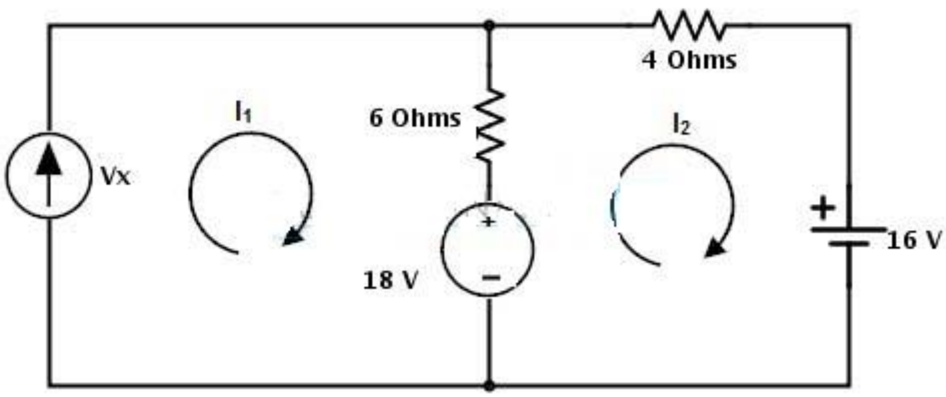
Step 1: In the circuit there is a possibility to change the current source to a voltage source on right hand side source with parallel resistance. The current source is converted into a voltage source by placing the same value of resistor in series with a voltage source and the voltage in that source is determined as

$Vs = Is\ Rs$

$= 4\times 4 = 16$ Volts



Step 2: Assign the branch currents as I1 and I2 to the respective branches or loops and represent the direction of currents as shown below.



Step 3: Apply the KVL to each mesh in the given circuit

Mesh -1:

$Vx - 6 \times (I1 - I2) - 18 = 0$

Substituting I1 = 12 A

$Vx + 6I2 = 90$…………………… (1)

Mesh – 2:

$18 - 6 \times (I2 - I1) - 4 \times I2 - 16 = 0$

2 – 10 × I2 + 6(12) = 0

I2 = 74/ 10

= 7.4 Amps

Substituting in equation 1 we get

Vx = 90 – 44.4

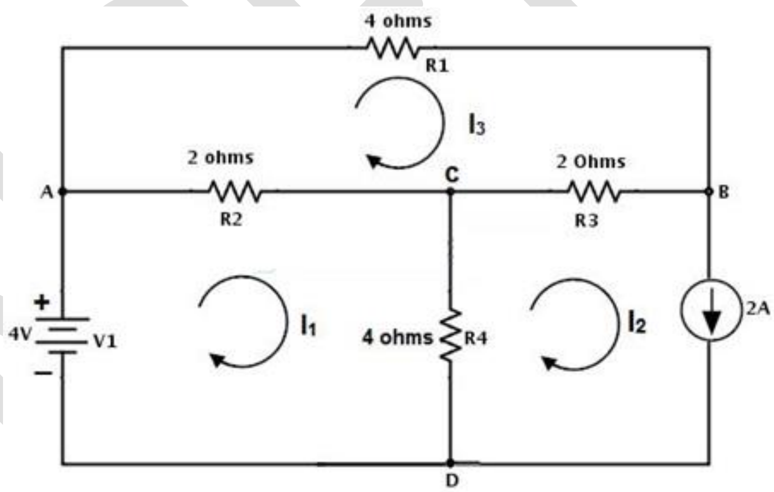
= 45.6 Volts

Example 2:

Consider the below circuit where we determine the voltage across the current source and a branch current Iac. Assign the directions as shown below and note that current is assigned opposite to the source current in second loop.

By applying KVL to the first mesh we get

V1 – R2 (I1 – I 3) – R4 (I1 – I 2) = 0



4 – 2 I1 – 2I3 – 4I1 – 4I2 = 0

-6I1 – 2I3 = 4 ……………(1)

By applying KVL to the second mesh we get

−Vc – R4(I 2 – I1) – R3 (I 2 – I 3) = 0

$-V_c = 4I_2 - 4I_1 + 2I_2 - 2I_3 = 0$

$-V_c = -4I_1 + 6I_2 - 2I_3$

But $I_2 = -2$ A, then

$-V_c = -4I_1 - 12 - 2I_3$ ………………….(2)

By applying KVL to the third mesh we get

$-R_1 I_3 - R_3(I_3 - I_2) - R_2(I_3 - I_1) = 0$

$-4I_3 - 2I_3 + 2I_2 - 2I_3 + 2I_1 = 0$

$-8I_3 - 4 + 2I_1 = 0$ (by substituting $I_2 = -2$ A)

$2I_1 - 8I_3 = 4$ …………………(3)

By solving 1 and 3 equations we get $I_3 = -0.615$ and $I_1 = 4.46$

Therefore, the voltage $V_c = 4(4.46) + 12 + 2(-0.615)$

$V_c = 28.61$ V

And the branch current $I_{ac} = I_1 - I_3$

$I_{ac} = 5.075$ amps

Likewise we can find every branch current using the mesh analysis.

Example: 3 Using mesh analysis, obtain the current through the 10V battery for the circuit shown in figure 1.

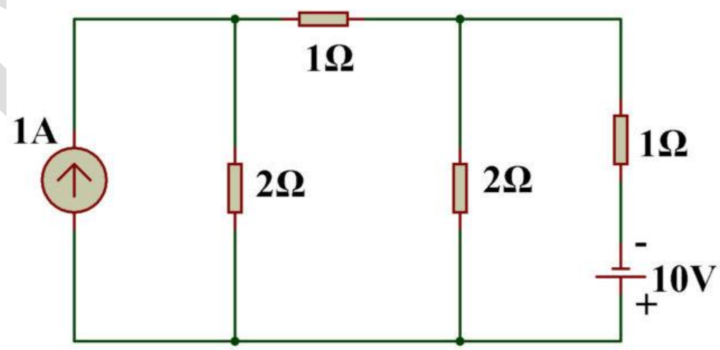


Figure: 1

Solution: The current source is first converted to an equivalent voltage source and the loop currents are named (Figure 2).

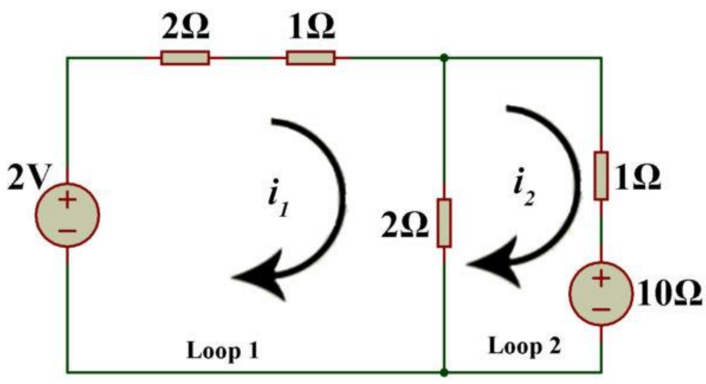


Figure: 2

Applying KVL in loop-1,

$$-2 + 3i_1 + (i_1 - i_2)2 = 0$$

or, $5i_1 - 2i_2 = 2$ .....(1)

and in loop-2,

$$2(i_2 - i_1) + i_2 - 10 = 0$$

or, $-2i_1 + 3i_2 - 10 = 0$ .....(2)

Solving equations (1) & (2),

$i_2 = 4.91A$ and $i_1 = 2.36A$

∴ Current of the 10V battery is 4.91A which enters the battery through –ve terminal as shown.

Example: 4 In figure 5, obtain the mesh equations. If $e_1 = e_2 = e_3 = 1V$ and all resistances are equal to each other, being 1Ω each, what would be the loop currents?

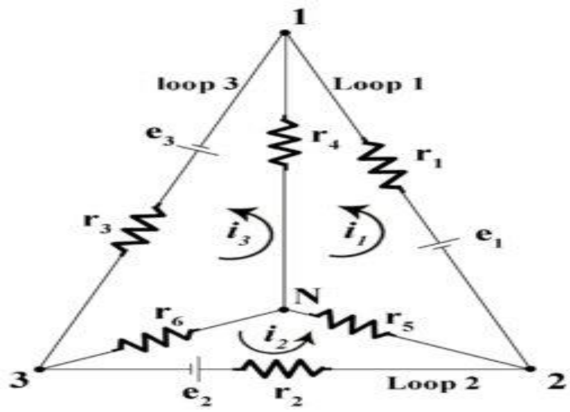


Figure: 5

Solution:

Let the loop currents be i_1, i_2, and i_3.

The loop equations are given below:

For loop-1

$$i_1 r_1 + (i_1 - i - 3)r_4 + (i_1 - i_2)r_5 = e_1$$

or, $i_1(r_1 + r_4 + r_5) - i_2 r_5 - i_3 r_4 = e_1$ …..(i)

For loop-2

$$(i_2 - i_1)r_5 + (i_2 - i_3)r_6 + i_2 r_2 = e_2$$

or, $-i_1 r_5 + i_2(r_2 + r_5 + r_6) - r_6 i_3 = e_2$ …..(ii)

For loop-3

$$i_3 r_3 + (i_3 - i_2)r_6 + (i_3 - i_1)r_4 = e_3$$

or, $-i_1 r_4 - i_2 r_6 + i_3(r_3 + r_4 + r_6) = e_3$ …..(iii)

If $e_1 = e_2 = e_3 = 1V$, and all resistance are equal, from symmetry it is evident that

$i_1 = i_2 = i_3 = i$

Thus for loop-1

$e_1 = 1 = ir = 1 \times i$

$\therefore$ I = 1A

The loop currents in all loops will be identical and equal to 1A for each loop

MESH MATRIX METHOD

- R_1, R_2, R_3, R_4 and R_5 are the various resistances
- V_1 and V_2 are the voltage source
- I_1 is the current flowing in the mesh ABFEA
- I_2 is the current flowing in the mesh BCGFB
- I_3 is the current flowing in the mesh CDHGC

The direction of the current is assumed in the clockwise for simplicity in solving the network.

Steps for Solving Network by Mesh Current Method

Considering the above circuit diagram, the following steps are given below to solve the circuit by the Mesh Current method.

Step 1 – First of all, identify the independent circuit meshes or loop. As there is three mesh in the circuit diagram shown above which are considering.

Step 2 – Assign a circulating current to each mesh as shown in circuit diagram where I_1, I_2 and I_3 are flowing in each mesh.

It is preferable to assign the same direction of all the currents and in a clockwise direction for making the calculation easier.

Step 3 – Now, write the KVL equation for each mesh.

As there are three meshes in the circuit, there will be three KVL equations as shown below

Applying KVL in the mesh ABFEA

$$I_1R_1 + (I_1 - I_2)R_2 = V_1$$

By rearranging the equation, we will get an equation (1)

$$I_1(R_1 + R_2) + I_2(-R_2) + I_3(0) = V_1 \dots\dots\dots\dots (1)$$

Applying KVL in the mesh BCGFB

$$I_2R_3 + (I_2 - I_3)R_4 + (I_2 - I_1)R_2 = 0 \quad \text{or}$$

$$I_1(-R_2) + I_2(R_2 + R_3 + R_4) + I_3(-R_4) = 0 \;\ldots\ldots\ldots(2)$$

Applying KVL in the mesh CDHGC

$$I_3R_5 + V_2 + (I_3 - I_2)R_4 = 0 \quad \text{or}$$

$$I_1(0) + I_2(-R_4) + I_3(R_4 + R_5) = -V_2 \;\ldots\ldots\ldots(3)$$

Step 4 – Now solve equations (1) (2) and (3) simultaneously to get the value of current I_1, I_2 and I_3.

By knowing the mesh currents, we can determine the various voltages and currents in the circuit.

Matrix Form

The above circuit can be solved by the Matrix method also, as shown below

The above equations (1), (2) and (3) in matrix form can be expressed as

$$\begin{bmatrix} R_1 + R_2 & -R_2 & 0 \\ -R_2 & R_2 + R_3 + R_4 & -R_4 \\ 0 & -R_4 & R_5 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} V_1 \\ 0 \\ -V_2 \end{bmatrix} \;\ldots\ldots\ldots(4)$$

Thus, the equation (4) can be solved to get the values it the various currents.

It is seen from the equation (4) that the resistance matrix [R] is symmetric, i.e.

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} \pm V_1 \\ \pm V_2 \\ \pm V_3 \end{bmatrix} \;\ldots\ldots\ldots\ldots\ldots(5)$$

Equation (5) can be written as:

$$[R][I] = [V]$$

Where,

[R] is the mesh resistance

[I] is the column vector of mesh currents and

[V] is the column vector of the algebraic sum of all the source voltages around the mesh.

NODE ANALYSIS/NODE VOLTAGE METHOD

Definition of Nodal Analysis

Nodal analysis is a method that provides a general procedure for analyzing circuits using node voltages as the circuit variables. **Nodal Analysis** is also called the **Node-Voltage Method**. Some Features of Nodal Analysis are as

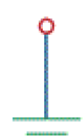
- **Nodal Analysis** is based on the application of the Kirchhoff's Current Law (KCL).
- Having 'n' nodes there will be 'n-1' simultaneous equations to solve.
- Solving 'n-1' equations all the nodes voltages can be obtained.
- The number of non reference nodes is equal to the number of Nodal equations that can be obtained.

Types of Nodes in Nodal Analysis

- Non Reference Node – It is a node which has a definite Node Voltage. E.g. Here Node 1 and Node 2 are the Non Reference nodes
- Reference Node – It is a node which acts a reference point to all the other node. It is also called the Datum Node.

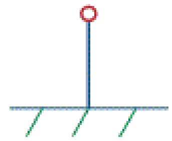
Types of Reference Nodes

1. Chassis Ground – This type of reference node acts a common node for more than one circuits.



2. Earth Ground – When earth potential is used as a reference in any circuit then this type of

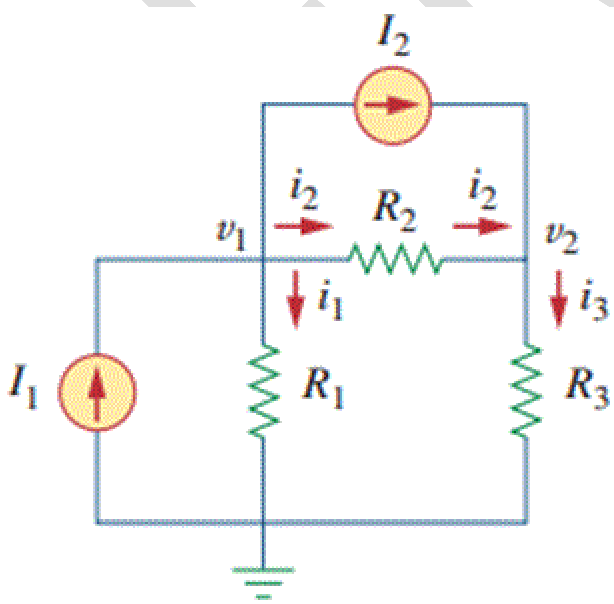
reference node is called Earth Ground.



Solving of Circuit Using Nodal Analysis

Basic Steps Used in Nodal Analysis

1. Select a node as the reference node. Assign voltages V_1, V_2… V_{n-1} to the remaining nodes. The voltages are referenced with respect to the reference node.
2. Apply KCL to each of the non reference nodes.
3. Use Ohm's law to express the branch currents in terms of node voltages.



Node Always assumes that current flows from a higher potential to a lower potential in resistor. Hence, current is expressed as follows

$$I = \frac{V_{high} - V_{low}}{R}$$

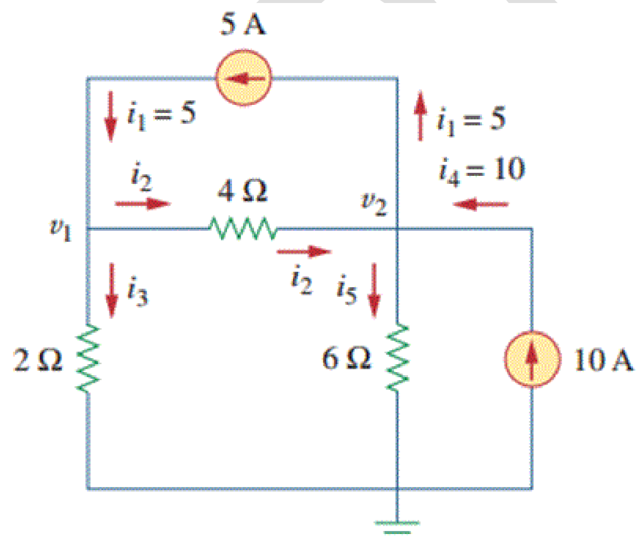
IV. After the application of Ohm's Law get the 'n-1' node equations in terms of node voltages and resistances.

V. Solve 'n-1' node equations for the values of node voltages and get the required node Voltages as result.

Nodal Analysis with Current Sources

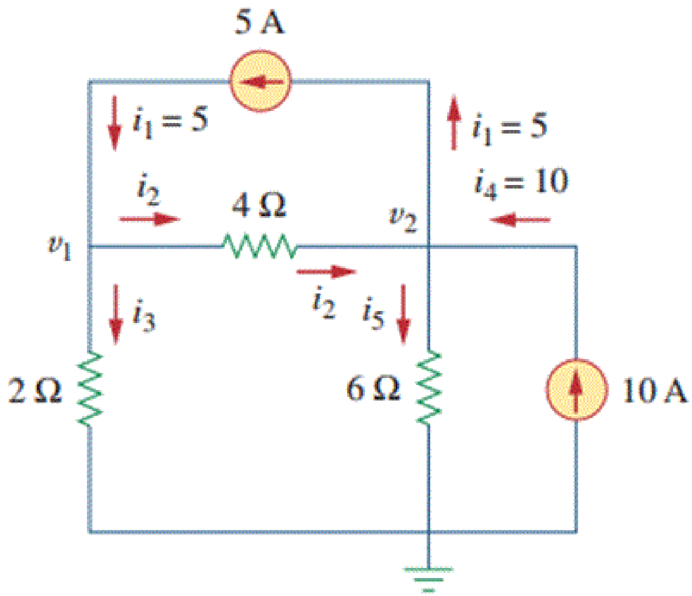
Nodal analysis with current sources is very easy and it is discussed with a example below.

Example: Calculate Node Voltages in following circuit



In the following circuit we have 3 nodes from which one is reference node and other two are non reference nodes – Node 1 and Node 2.

Step I. Assign the nodes voltages as v_1 and $_2$ and also mark the directions of branch currents with respect to the reference nodes



Step II. Apply KCL to Nodes 1 and 2

KCL at Node 1 $$i_1 = i_2 + i_3 \cdots\cdots(1)$$

KCL at Node 2 $$i_2 + i_4 = i_1 + i_5 \cdots\cdots(2)$$

Step III. Apply Ohm's Law to KCL equations

• Ohm's law to KCL equation at Node 1

$$i_1 = i_2 + i_3 \Rightarrow 5 = \frac{v_1 - v_2}{4} + \frac{v_1 - 0}{2}$$

Simplifying the above equation we get,

$$3v_1 - v_2 = 20 \cdots\cdots(3)$$

• Now, Ohm's Law to KCL equation at Node 2

$$i_2 + i_4 = i_1 + i_5 \Rightarrow \frac{v_1 - v_2}{4} + 10 = 5 + \frac{v_2 - 0}{6}$$

Simplifying the above equation we get

$$-3v_1 + 5v_2 = 60 \cdots\cdots(4)$$

Step IV. Now solve the equations 3 and 4 to get the values of v_1 and v_2 as,
Using elimination method

$$\begin{aligned} 3v_1 - v_2 &= 20 \\ -3v_1 + 5v_2 &= 60 \\ \Rightarrow 4v_2 = 80 \Rightarrow v_2 &= 20\ Volts \end{aligned}$$

And substituting value v_2 = 20 Volts in equation (3) we get-

$$3v_1 - 20 = 20 \Rightarrow v_1 = \frac{40}{3} = 13.333\ Volts$$

Hence node voltages are as v_1 = 13.33 Volts and v_2 = 20 Volts.

Nodal Analysis with Voltage Sources

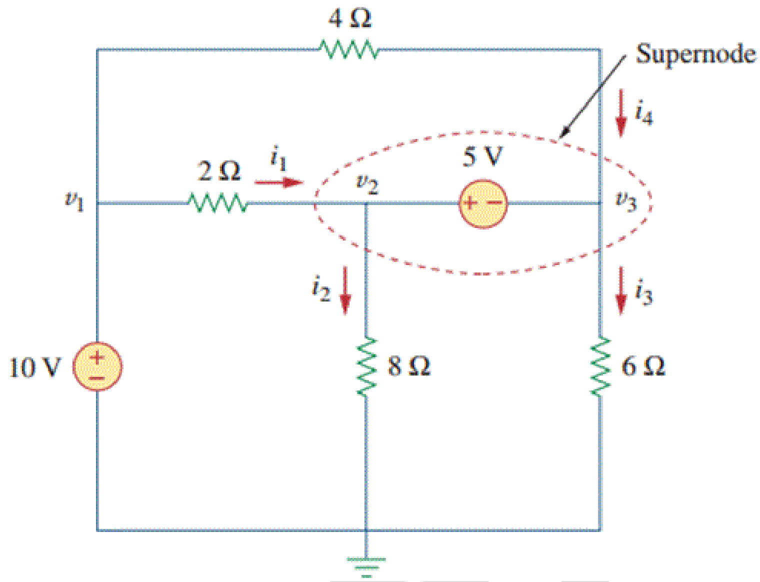
Case I. If a voltage source is connected between the reference node and a non reference node, we simply set the voltage at the non-reference node equal to the voltage of the voltage source and its analysis can be done as we done with current sources. V_1 = 10 Volts.

Case II. If the voltage source is between the two non reference nodes then it forms a supernode whose analysis is done as following

Supernode Analysis

Definition of Super Node

Whenever a voltage source (Independent or Dependent) is connected between the two non reference nodes then these two nodes form a generalized node called the Super node. So, Super node can be regarded as a surface enclosing the voltage source and its two nodes.



In the above Figure 5V source is connected between two non refer

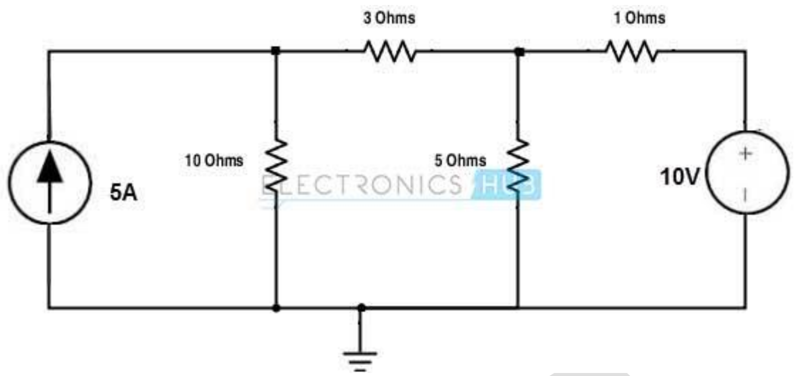
ence nodes Node – 2 and Node – 3. So here Node – 2 and Node – 3 form the Super node.

Properties of Supernode

- Always the difference between the voltage of two non reference nodes is known at Supernode.
- A supernode has no voltage of its own
- A supernode requires application of both KCL and KVL to solve it.
- Any element can be connected in parallel with the voltage source forming the supernode.
- A Supernode satisfies the KCL as like a simple node.

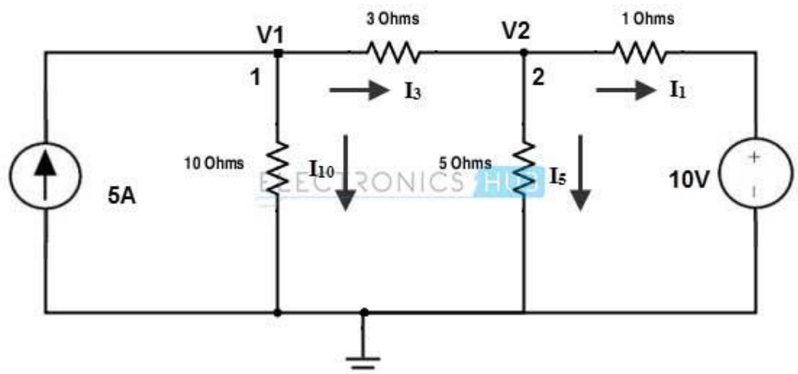
Example 1

Determine the node voltages and currents in each branch using nodal analysis method in the given circuit.



The given circuit contains a voltage source. This can be transformed to current source or can be analysed directly without any transformation. Now let us calculate the nodal voltages without any transformation.

As a first step in nodal analysis, we have to choose and label the nodes present in the given circuit. By choosing the bottom node as reference node, we have two another nodes in the given circuit. So these nodes are 92abeled as V1 and V2 as shown in below figure. And also current directions in each branch are represented.



By applying KCL at node 1, we get

5 = I3 + I10

5 = (V1/10) + (V1 – V2/3)

13V1 – 10V2 = 150 ………(1)

By applying KCL at node 2, we get

I3 = I5 + I1

(V1 – V2/3) = (V2/5) + (V2 – 10/1)

5V1 – 23V2 = -150 ……..(2)

By solving above two equations, we get

V1 = 19.85 Volts and V2 = 10.9 Volts

The currents in each branch is given as

I10 = V1/10

= 19.85/10 = 1.985

I3 = V1 – V2/3

= 19.85 – 10.9/3

= 2.98 A

I5 = V2/5

= 10.9/5

= 2.18 A

I1 = V2 – 10

= 10.9 – 10

= 0.9 A

Example 2: Using Nodal method, find the current through resistor r_2 (Figure 1).

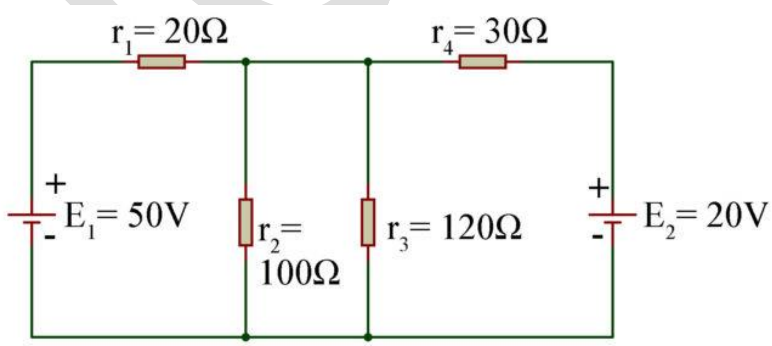


Figure: 1

Solution: Let us redraw the circuit with naming of the nodes and branch current as shown in figure 2.

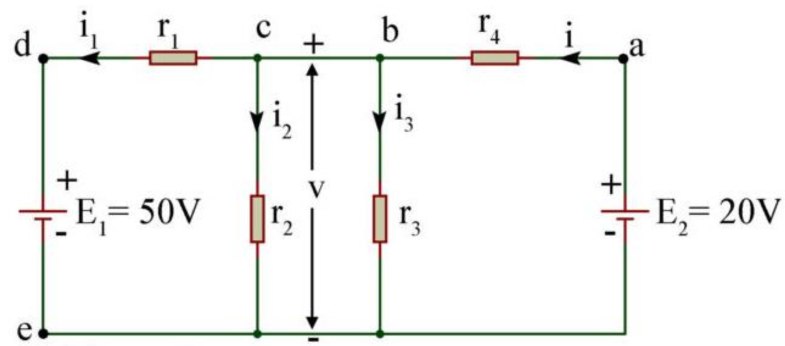


Figure: 2

At node "b", $i = i_1 + i_2 + i_3$ (electrically nodes b and c are same)

Assuming the polarity of the voltage v at node c or b, we thus get.

$$\frac{20 - v}{r_4} = \frac{v - 50}{r_1} + \frac{v}{r_2} + \frac{v}{r_3}$$

or, $$\frac{v - 20}{30} + \frac{v - 50}{20} + \frac{v}{100} + \frac{v}{120} = 0$$

$$\therefore v = 31.18V$$

$$\therefore i_2 = \frac{v}{r_2} = \frac{31.18}{100}A = 0.3118A$$

i.e. current through r_2 = 311.8mA.

Example 4: In the circuit of figure 7, find the current in 1Ω resistor.

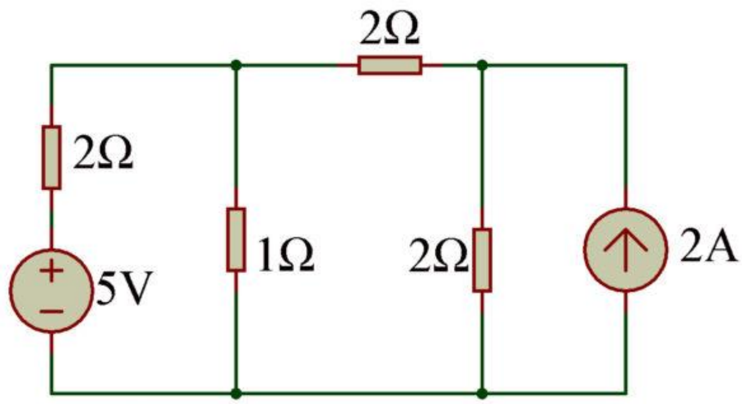


Figure: 7

Solution:

Let us first convert the current source of figure 7 to voltage source and draw the equivalent network (figure 8). Let the +ve voltage at node (1) be v_1 V.

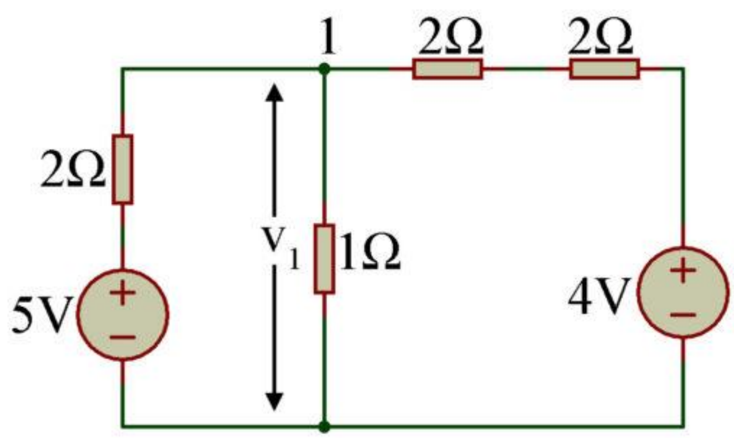


Figure: 8

∴Using nodal analysis,

$$\frac{v_1}{1} + \frac{v_1 - 5}{2} + \frac{v_1 - 4}{4} = 0$$

or, $v_1 = 2V$

Hence, the current through 1Ω resistor is

$$\frac{v_1}{1} = 2A$$

MODULE II

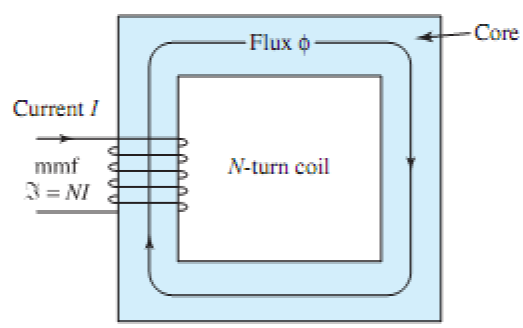
ELEMENTARY CONCEPTS OF MAGNETIC CIRCUITS, ELECTROMAGNETIC INDUCTION AND AC FUNDAMENTALS

INTRODUCTION TO MAGNETIC CIRCUITS

Definition

The closed path followed by the magnetic flux is magnetic circuit. All electric power machinery such as **generator**, **transformer**, **motors** depend for their operation on the magnetic circuits.

A magnetic circuit consists of a structure composed for the most of high permeability magnetic material. The core is assumed to be composed of magnetic material whose permeability is much greater than that of the surrounding air. The core is of uniform cross-section and is excited by a winding having N turns and carrying a current of I amperes. This winding develops a magnetic field in the core. The magnetic field is in terms of flux lines which form closed loops interlinking with the winding.



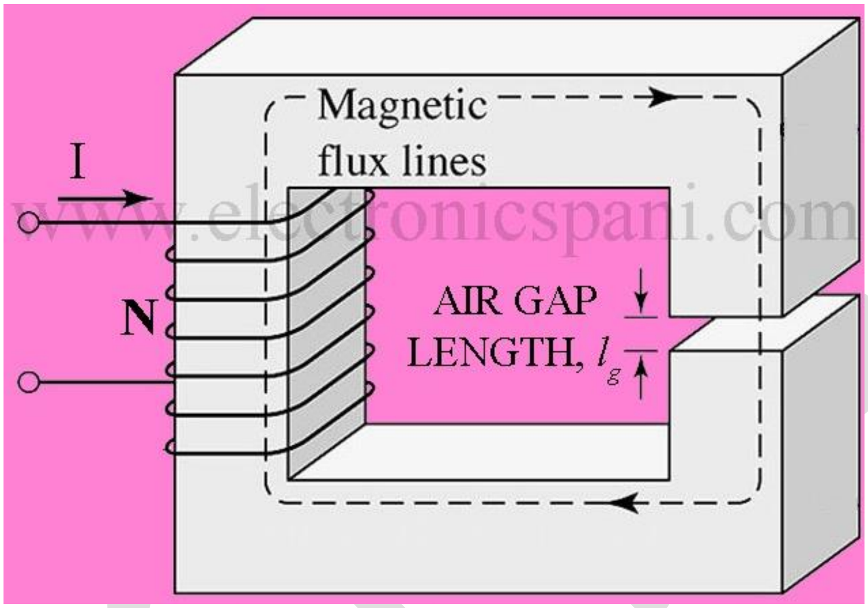
Simple Magnetic Circuit

Magnetic Circuit Basics

A closed path followed by magnetic flux is known as a **magnetic circuit**. In a magnetic circuit, flux starts from one point and finishes at the same point. A magnetic circuit usually consists of magnetic materials having high permeability such as iron, soft-steel, etc. since they offer small opposition to magnetic flux.

Magnetic Circuits with Air-Gaps.

Energy-conversion devices which incorporate a moving element have necessarily air gaps in their magnetic circuits. Air-gaps are also provided in the magnetic circuits to avoid Saturation. A magnetic circuit with an air gap is shown in Fig. 2. An air-gap is nothing else but a volume of air between two magnetic surfaces. The length of air gap lg equals the distance between the two magnetic surfaces. The area of x-section of any one of the surfaces gives the air-gap area ag. When the air-gap length lg is much smaller than the dimensions of the adjacent core faces, the magnetic flux \phi is constrained essentially to reside in the core and the air gap and is continuous throughout the magnetic circuit.



magnetic circuit with air gap

Thus, the configuration shown in Fig. 2 can be analyzed as a magnetic circuit with two series components, a magnetic or iron core of permeability \mu and mean length li and an air-gap of permeability \mu_0 and length lg. Since the permeability of air is constant, the air-gap is a linear part of the magnetic circuit and the flux density in the air-gap is proportional to the mmf across the air-gap. The necessary mmf is calculated separately for the air-gap and the iron portions and then added to determine the total mmf.

The magnetic flux is usually produced by an electric current through a solenoid (having a large number of turns. There are three types of magnetic circuits:

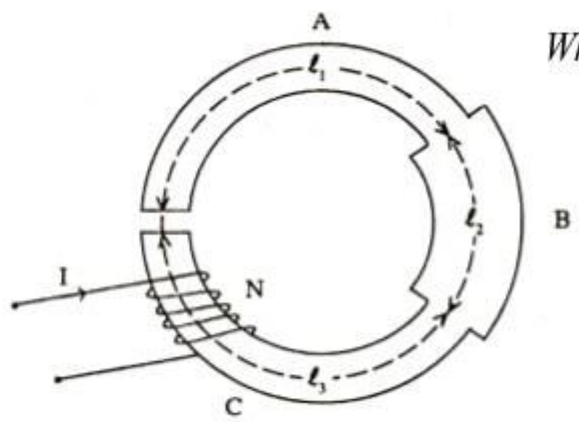
- Series Magnetic Circuit
- Parallel Magnetic Circuit
- Series-parallel Magnetic Circuits

SERIES MAGNETIC CIRCUIT

A magnetic circuit that has many parts of different dimensions and materials connected in series is called a series magnetic circuit.

Consider a composite magnetic circuit consisting of three parts having different lengths, area of cross-sections and relative permeability's. It also has an air-gap.

In this case, the reluctance of each part will be different depending upon the dimensions and relative permeability's of that part. The total reluctance will be the sum of the reluctance of individual parts. The same flux will flow through complete circuits.



$$\text{Total Reluctance} \quad S = S_1 + S_2 + S_3 + S_g$$

$$\text{Where} \quad S_1 = \frac{l_1}{\mu_0 \mu_{r1} a_1}$$

$$S_2 = \frac{l_2}{\mu_0 \mu_{r2} a_2}$$

$$S_3 = \frac{l_3}{\mu_0 \mu_{r3} a_3}$$

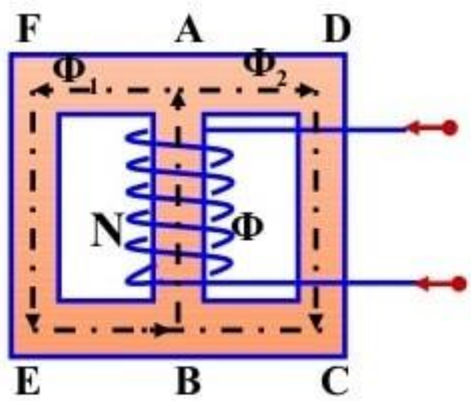
$$S_g = \frac{l_g}{\mu_0 \mu_{rg} a_g}$$

$$\text{mmf} = \left(\varphi_1 S_1 + \varphi_2 S_2 + \varphi_3 S_3 + \varphi_g S_g\right) = \left(\frac{B_1 l_1}{\mu_0 \mu_{r1}} + \frac{B_2 l_2}{\mu_0 \mu_{r2}} + \frac{B_3 l_3}{\mu_0 \mu_{r3}} + \frac{B_g l_g}{\mu_0 \mu_{rg}}\right)$$

$$\text{Total mmf} = H_1 l_1 + H_2 l_2 + H_3 l_3 + H_g l_g$$

PARALLEL MAGNETIC CIRCUIT

A magnetic circuit that has more than one path for the magnetic flux is called a **parallel magnetic circuit**. It is similar to a parallel electric circuit that has more than one for electric current to flow.



$$S_{AB} = \frac{l}{\mu_0 \mu_{r_1} a}; S_{ADCB} = \frac{l_2}{\mu_0 \mu_{r2} a_2}; S_{AFEB} = \frac{l_1}{\mu_0 \mu_{r3} a_3}; \quad \phi = \phi_1 + \phi_2$$

$$\text{Total mmf required} = \text{Path AB mmf} + (\text{Path AFEB or ADCB mmf})$$

$$MMF_{Total} = \phi S_{AB} + (\phi_1 S_{AFEB} \text{ or } \phi_2 S_{ADCB}),$$

$$\text{Where } \phi_1 S_{AFEB} = \phi_2 S_{ADCB}$$

Consider a parallel magnetic circuit shown in Figure. A current-carrying coil is wound on the central limb. The flux set up by this coil is divided at A into two paths i.e.

- Flux ϕ_1 passes along the path AFEB,
- Flux ϕ_2 passes along the path ADCB

It is clear that $\phi = \phi_1 + \phi_2$

Here the two magnetic paths AFEB and ADCB are in parallel, the total MMF required for this parallel circuit will be equal to the MMF required for anyone of the above said paths.

MAGNETIC FLUX DENSITY (B)

The flux per unit area is defined as the *magnetic flux density*. It is measured in a plane perpendicular to flux.

Magnetic Flux Density, $\mathbf{B = \varphi \div A}$

Units: Weber per meter square (**Wb/m^2**) or **tesla(T).**

MAGNETIC FIELD INTENSITY (H)

The magnetic field strength or magnetic field intensity is given by MMF per unit length of the magnetic circuit.

Magnetic Field Intensity, **H = (N*I*) ÷ l**

where N = Number of turns of magnetizing coil

I = Current through the coil

l = length of magnetic material in meters

Units: **AT/m.**
The magnetic field intensity is also known as magnetic field strength or magnetizing force.

PERMEABILITY (μ)

The ability of a material to carry the magnetic lines of flux is known as *permeability* of that material.

The magnetic lines of force can pass through high permeability materials like iron, steel, very easily. Low permeability materials like wood etc. don't allow the flux lines to pass through them easily.

Absolute Permeability

It is the ratio of flux density (B) in a particular medium to the magnetic field strength (H) which produces magnetic flux density. It is denoted by μ.

Absolute Permeability, $\mu = \mu_o \mu_r$

Units: Henry/meter **(H/m)**

PERMEABILITY OF THE AIR/SPACE/VACUUM(μ_O)

If a magnet is kept in air or vacuum, then the ratio of flux density (B) and magnetic field strength (H) is defined as the permeability of free space. It is denoted by μ_o.

Permeability of Free Space, $\mu_o = 4\pi \times 10^{-7}$ **H/m**

RELATIVE PERMEABILITY (μ_R)

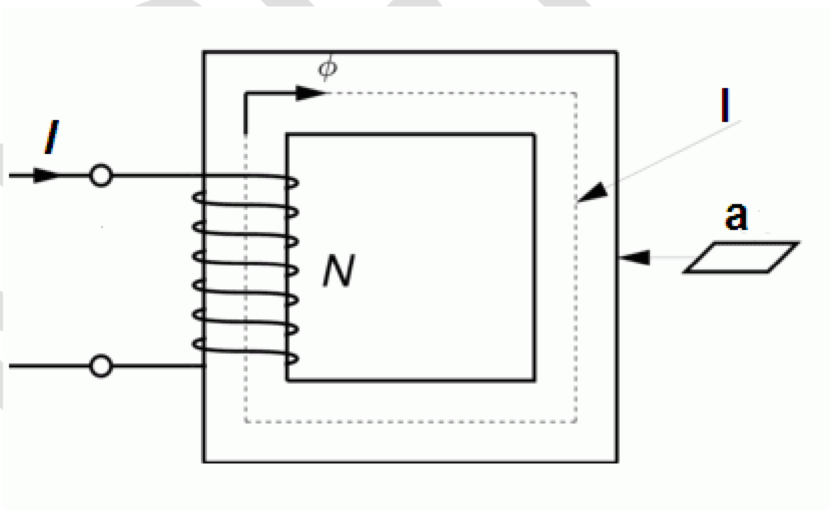
The ratio of permeability of material to the permeability of vacuum or air is known as *relative permeability*.

Relative Permeability, $\mu_r = \mu \div \mu_o$

It has no units.

The relative permeability of vacuum, air and all non-magnetic materials is 1. The relative permeability of all the magnetic materials is very high. For example, the relative permeability of permalloy (nickel 78% and iron 22%) is about 50000.

MAGNETO-MOTIVE FORCE (MMF)



The *magneto-motive force* is the driving force which produces the magnetic flux. The magnetic field intensity (H) is decided by MMF.

Magneto-motive Force, **MMF = N*I***

where N = Number of turns of magnetizing coil

I = Current through the coil

Units: Ampere Turns (**AT**)

RELUCTANCE (S)

It is opposition offered to the flow of magnetic flux by the magnetic material.

Unit: **AT/Wb**

Reluctance, S = l ÷ (μ x a)

where l = length of the magnetic path in meters.

a = area of the cross-section of magnetic path in meter square.

μ = absolute permeability of medium in H/m.

$= \mu_o \mu_r$

Therefore, Reluctance, $\mathbf{S = l \div (\mu_o \mu_r a)}$

The reluctance is also given by the ratio of the MMF and the amount of flux produced.

i.e. Reluctance, S = MMF ÷ flux

Reluctance, **S = (N*I*) ÷ φ**

PERMEANCE

The *permeance* of a material represents the ease with which magnetic flux can be produced in that material. It is reciprocal of reluctance. Its unit is Wb/AT or henry.

MAGNETIC SUSCEPTIBILITY

The magnetization of a material is proportional to the field and the proportionality constant is called the magnetic susceptibility. In other words, it can be defined as the ratio of magnetization **M** to magnetizing force **H** i.e.

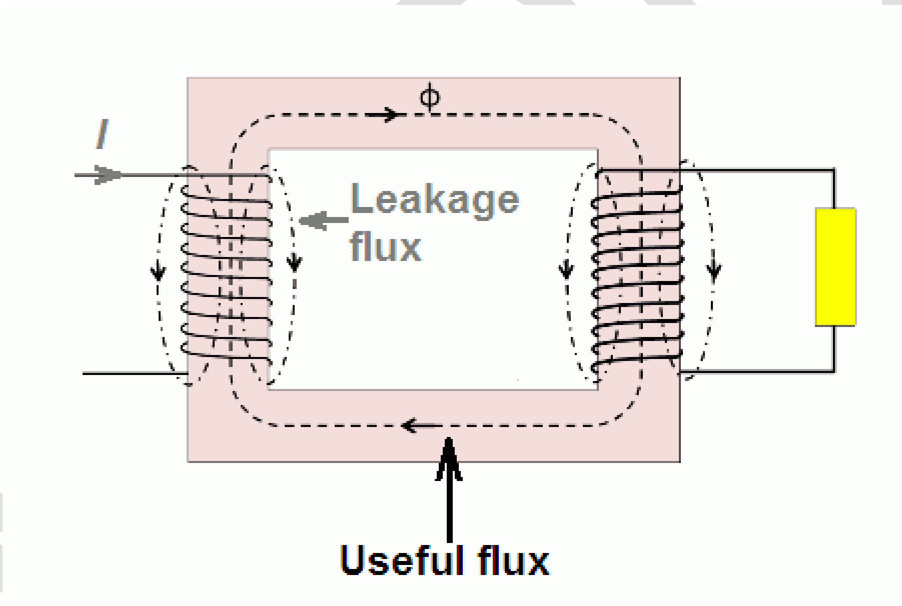
Magnetic Susceptibility, $\mathbf{X_m = M/H}$

It is a dimensionless quantity. It is a measure of how easily a material is magnetized in a magnetizing field. Its value for vacuum is zero as there can be no magnetization in the vacuum.

We can classify materials in terms of $\mathbf{X_m}$. Materials with positive values of $\mathbf{X_m}$ are paramagnetic and those with negative values of $\mathbf{X_m}$ are diamagnetic. For ferromagnetic materials, $\mathbf{X_m}$ is positive and very large.

LEAKAGE FLUX

The part of the total magnetic flux which flows through the magnetic circuit is called useful magnetic flux. However, the magnetic flux which does not completely pass through the magnetic path, but partially passes through the air is called *leakage magnetic flux*.



Mathematically, $\varphi_{\text{total}} = \varphi_{\text{useful}} + \varphi_{\text{leakage}}$

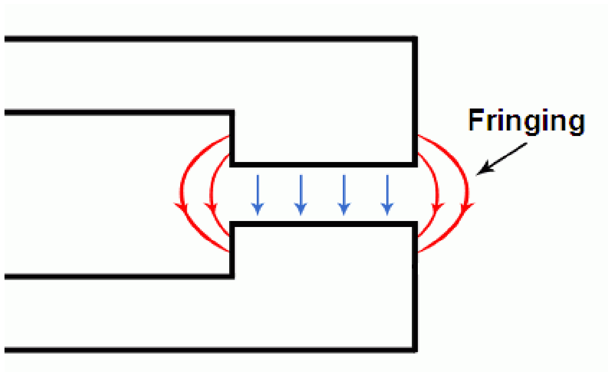
Leakage Factor (λ)

The ratio of total flux produced to the useful flux is called leakage factor or leakage coefficient. Leakage factor, $\lambda = \varphi_{\text{total}} / \varphi_{\text{useful}}$

The value of *leakage factor* is always greater than unity. Typical values of leakage factor are from 1.12 to 1.25. In the magnetic circuits, the magnetic leakage can be minimized by placing the exciting coils as close as possible to the points where the flux is to be utilized.

FRINGING

The magnetic lines of force repel each other while passing through a non-magnetic material. Due to this when the flux lines cross the air gap, they tend to bulge outwards. This effect is known as *fringing*.



The effect of fringing is to make the effective air gap area larger than that of magnetic path and consequently, the flux density in the air gap is reduced. The effect of fringing depends upon the length of the air gap. To minimize fringing, the air gap length is kept as small as possible. The effect of fringing can be neglected if air gap length is very small as compared to its width.

EXAMPLE PROBLEMS

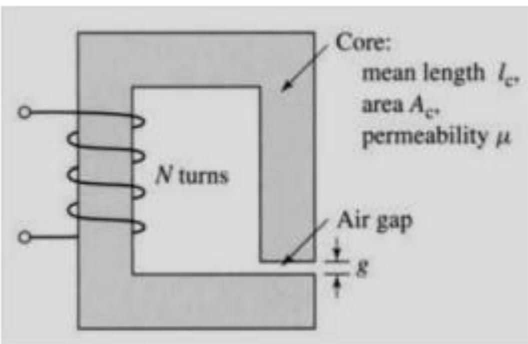
1. A magnetic circuit with a single air gap is shown in Fig. 1.24. The core dimensions are:

Cross-sectional area $A_c = 1.8 \times 10^{-3}\ m^2$

Mean core length $l_c = 0.6$ m

Gap length $g = 2.3 \times 10^{-3}$ m

$N = 83$ turns



Assume that the core is of infinite permeability (m -> ¥) and neglect the effects of fringing fields at the air gap and leakage flux. (a) Calculate the reluctance of the core, R_e and that of the gap R_g. For a current of i = 1.5 A, calculate (b) the total flux ϕ, (c) the flux linkages λ of the coil, and (d) the coil inductance L.

Solution:

$R_c = 0$ since $\mu \to \infty$

$$R_g = \frac{g}{\mu_0 A_c} = \frac{2.3\times10^{-3}}{4\pi\times10^{-7}\times1.8\times10^{-3}} = 1.017\times10^{6}\ \text{A/Wb}$$

$$\phi = \frac{Ni}{R_c + R_g} = \frac{83\times1.5}{1.017\times10^{6}} = 1.224\times10^{-4}\ \text{Wb}$$

$$\lambda = N\phi = 1.016\times10^{-2}\ \text{Wb}$$

$$L = \frac{\lambda}{i} = \frac{1.016\times10^{-2}}{1.5} = 6.773\ \text{mH}$$

Solution:

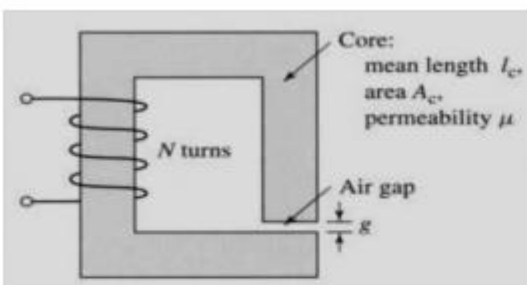
$R_c = 0$ since $\mu \to \infty$ $\qquad R_g = \frac{g}{\mu_0 A_c} = \frac{2.3\times10^{-3}}{4\pi\times10^{-7}\times1.8\times10^{-3}} = 1.017\times10^6$ A/Wb

$$\phi = \frac{Ni}{R_c + R_g} = \frac{83\times1.5}{1.017\times10^6} = 1.224\times10^{-4} \text{ Wb}$$

$$\lambda = N\phi = 1.016\times10^{-2} \text{ Wb}$$

$$L = \frac{\lambda}{i} = \frac{1.016\times10^{-2}}{1.5} = 6.773 \text{ mH}$$

2. Consider the magnetic circuit of with the dimensions of Problem 1.1. Assuming infinite core permeability, calculate (a) the number of turns required to achieve an inductance of 12 mH and (b) the inductor current which will result in a core flux density of 1.0 T.



Solution:

$$L = \frac{N^2}{R_g} = 12\times10^{-3} \text{ mH} \quad \Rightarrow \quad N = \sqrt{12\times10^{-3}\times1.017\times10^6} = 110.47 \quad \Rightarrow \quad N = 110 \text{ turns}$$

$$B_c = B_g = 1.0 \text{ T} \quad \Rightarrow \quad \phi = B_g A_c = 1.8\times10^{-3} \text{ Wb}$$

$$i = \frac{\lambda}{L} = \frac{N\phi}{L} = \frac{110\times1.8\times10^{-3}}{12\times10^{-3}} = 16.5 \text{ A}$$

ELECTRIC CIRCUIT VS MAGNETIC CIRCUITS

The Difference between the Magnetic and Electric Circuit are explained considering various factors like the basic definition, relation between Flux and Current, Reluctance and Resistance, EMF and MMF, different analogies of both the circuits. Like its density and intensity, laws applicable in the circuit, Magnetic and Electric lines, etc.

The Difference between Both the circuits are explained below in the tabulated form.

BASIS	MAGNETIC CIRCUIT	ELECTRIC CIRCUIT
Definition	The closed path for magnetic flux is called magnetic circuit.	The closed path for electric current is called electric circuit.
Relation Between Flux and Current	Flux = mmf/reluctance	Current = emf/ resistance
Units	Flux φ is measured in weber (wb)	Current I is measured in amperes
MMF and EMF	Magnetomotive force is the driving force and is measured in Ampere turns (AT) Mmf =∫ H.dl	Electromotive force is the driving force and measured in volts (V) Emf = ∫ E.dl
Reluctance and Resistance	Reluctance opposes the flow of magnetic flux S = l/aμ and measured in (AT/wb)	Resistance opposes the flow of current R = ρ. l/a and measured in (Ώ)
Relation between Permeance and Conduction	Permeance = 1/reluctance	Conduction = 1/ resistance
Analogy	Permeability	Conductivity
Analogy	Reluctivity	Resistivity
Density	Flux density B = φ/a (wb/m2)	Current density J = I/a (A/m2)

BASIS	MAGNETIC CIRCUIT	ELECTRIC CIRCUIT
Intensity	Magnetic intensity $H = NI/l$	Electric density $E = V/d$
Drops	Mmf drop = φS	Voltage drop = IR
Flux and Electrons	In magnetic circuit molecular poles are aligned. The flux does not flow, but sets up in the magnetic circuit.	In electric circuit electric current flows in the form of electrons.
Examples	For magnetic flux, there is no perfect insulator. It can set up even in the non magnetic materials like air, rubber, glass etc.	For electric circuit there are a large number of perfect insulators like glass, air, rubber, PVC and synthetic resin which do not allow it to flow through them.
Variation of Reluctance and Resistance	The reluctance (S) of a magnetic circuit is not constant rather it varies with the value of B.	The resistance (R) of an electric circuit is almost constant as its value depends upon the value of ρ. The value of ρ and R can change slightly if the change in temperature takes place
Energy in the circuit	Once the magnetic flux sets up in a magnetic circuit, no energy is expanded. Only a small amount of energy is required at the initial stage to create flux in the circuit.	Energy is expanding continuously, as long as the current flows through the electrical circuit. This energy is dissipated in the form of heat.
Applicable Laws	Khirchhoff flux and mmf law is followed	Khirchhoff voltage and current law is followed. (KVL and KCL)
Magnetic and Electric lines	Magnetic lines of flux starts from North pole and ends at South pole.	Electric lines or current starts from positive charge and ends on negative charge.

Magnetic Circuit

The closed path followed by magnetic lines of forces or we can say magnetic flux is called magnetic circuit. A magnetic circuit is made up of magnetic materials having high permeability such as iron, soft steel, etc. Magnetic circuits are used in various devices like electric motor, transformers, relays, generators galvanometer, etc.

Electric Circuit

The rearrangement by which various electrical sources like AC source or DC source, resistances, capacitance and another electrical parameter are connected is called electric circuit or electrical network.

Key Differences Between Magnetic and Electric Circuit

1. The closed path followed by the flux in the Magnetic Circuit, whereas in the Electric Circuit Current follows the closed path.

2. The unit of flux is Weber, and the unit of current is Ampere.

3. Magnetomotive force in the magnetic circuit is the driving force and is measured in Ampere-turns (AT). Electromotive force is the driving force in the electric circuit and is measured in volts (V).

4. Reluctance opposed the flow of magnetic flux S = l/aμ and measured in (AT/wb) and Resistance opposes the flow of current R = ρ. l/a and measured in (Ω).

5. In the magnetic circuit Permeance = 1/reluctance whereas in the electric circuit Conduction = 1/ resistance.

6. As in the magnetic circuit, there exists Permeability so as Conductivity in the electric circuit. Similarly, Reluctivity in magnetic circuit is known as Resistivity in the electric circuit.

7. In the magnetic circuit, molecular poles are aligned. The flux does not flow but sets up in the magnetic circuit. In electric circuit electric current flows in the form of electrons.

8. For magnetic flux, there is no perfect insulator. It can set up even in the non-magnetic materials like air, rubber, glass, etc. For electric circuit, there are a large number of perfect insulators like glass, air, rubber, PVC and synthetic resin which do not allow it to flow through them.

9. The reluctance (S) of a magnetic circuit is not constant rather it varies with the value of

B.The resistance (R) of an electric circuit is almost constant as its value depends upon the value of ρ. The value of ρ and R can change slightly if the change in temperature takes place.

10. Once the magnetic flux sets up in a magnetic circuit, no energy is expanded. Only a small amount of energy is required at the initial stage to create flux in the circuit. Energy is expanding continuously, as long as the current flows through the electrical circuit. This energy is dissipated in the form of heat.

11. Kirchhoff flux and MMF law is followed in the magnetic circuit whereas in the electric circuit Kirchhoff voltage and current law is followed. (KVL and KCL).

12. Magnetic lines of flux start from The North Pole and ends at the South Pole. Electric lines or current starts from the positive charge and ends on the negative charge.

ELECTROMAGNETIC INDUCTION

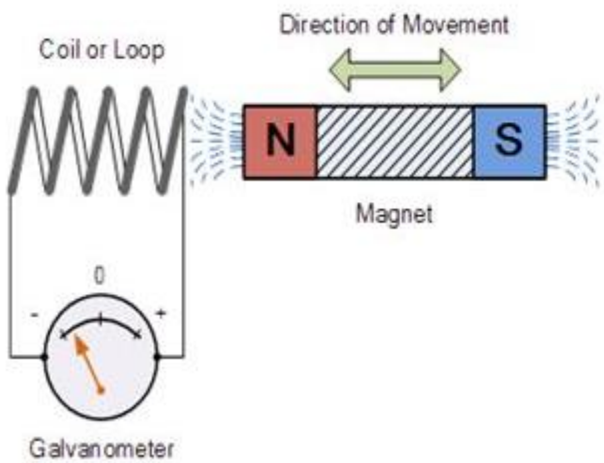
What is Electromagnetic Induction?

Electromagnetic Induction was **discovered by Michael Faraday** in 1831 and James Clerk Maxwell mathematically described it as Faraday's law of induction.

Electromagnetic Induction is a current produced because of voltage production (electromotive force) due to a changing magnetic field.

This either happens when a conductor is placed in a moving magnetic field (when using AC power source) or when a conductor is constantly moving in a stationary magnetic field.

Michael Faraday arranged a conducting wire as per the setup given below, attached to a device to measure the voltage across the circuit. When a bar magnet was moved through the coiling, the voltage detector measures the voltage in the circuit.



Through his experiment, he discovered that there are certain factors that influence this voltage production. They are:

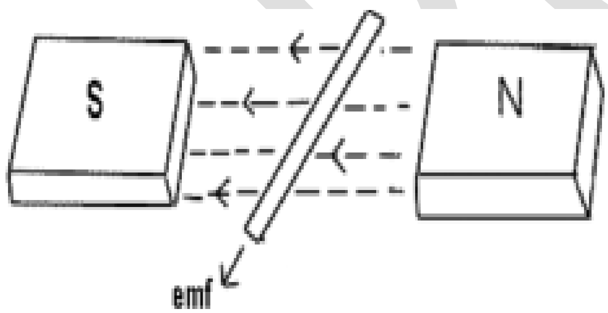
1. ***Number of Coils***: The induced voltage is directly proportional to the number of turns/coils of the wire. Greater the number of turns, greater is voltage produced
2. ***Changing Magnetic Field***: Changing magnetic field affects the induced voltage. This can be done by either moving the magnetic field around the conductor or moving the conductor in the magnetic field.

The induction of an electromotive force by the motion of a conductor across a magnetic field or by a change in magnetic flux in a magnetic field is called **'Electromagnetic Induction'.**

This either happens when a conductor is set in a moving magnetic field (when utilizing AC power source) or when a conductor is always moving in a stationary magnetic field.

This law of electromagnetic induction was found by **Michael Faraday.** He organized a leading wire according to the setup given underneath, connected to a gadget to gauge the voltage over the circuit. So when a bar magnet passes through the snaking, the voltage is measured in the circuit. The importance of this is a way of producing electrical energy in a circuit by using magnetic fields and not just batteries anymore. The machines like generators, transformers also the motors work on the principle of electromagnetic induction.

Faraday's law of Electromagnetic Induction



- **First law:** Whenever a conductor is placed in a varying magnetic field, EMF induces and this emf is called an induced emf and if the conductor is a closed circuit than the induced current flows through it.
- **Second law:** The magnitude of the induced EMF is equal to the rate of change of flux linkages.

Based on his experiments we now have Faraday's law of electromagnetic induction according to which the amount of voltage induced in a coil is proportional to the number of turns and the changing magnetic field of the coil.

So now, the induced voltage is as follows:

e = N × dΦdt

where,

e is the induced voltage

N is the number of turns in the coil

Φ is the magnetic flux

t is the time

Lenz's law of Electromagnetic Induction

Lenz law of electromagnetic induction states that, when an emf induces according to Faraday's law, the polarity (direction) of that induced emf is such that it opposes the cause of its production.

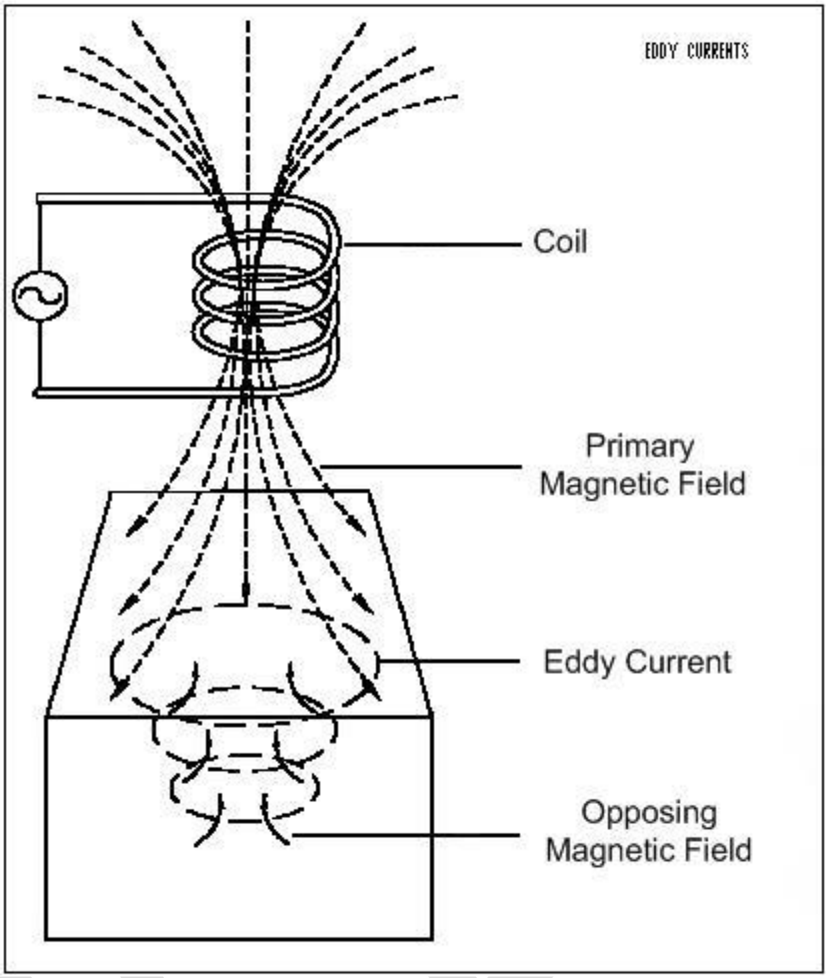
According to Lenz's law

E = -N (dΦ/ dt) (volts)

Eddy currents

By Lenz law of electromagnetic induction, the current swirls in such a way as to create a magnetic field opposing the change. Because of the tendency of eddy currents to oppose, eddy currents cause a loss of energy. Eddy currents transform more useful forms of energy, such as kinetic energy, into heat, which isn't generally useful. In many applications, the loss of useful energy is not particularly desirable, but there are some practical applications. Like:

- In the brakes of some trains. During braking, the brakes expose the metal wheels to a magnetic field which generates eddy currents in the wheels. The magnetic interaction between the applied field and the eddy currents slows the wheels down. The faster the wheels spin, the stronger is the effect, meaning that as the train slows the braking force is reduces, producing a smooth stopping motion.
- There are few galvanometers having a fixed core which are of nonmagnetic metallic material. When the coil oscillates, the eddy currents that generate in the core oppose the motion and bring the coil to rest.
- Induction furnace can be used to prepare alloys, by melting the metals. The eddy currents generated in the metals produce high temperature enough to melt it.



Applications of Electromagnetic Induction

1. Electromagnetic induction in AC generator
2. Electrical Transformers
3. Magnetic Flow Meter

FLEMMING RULE

Whenever a current carrying conductor comes under a magnetic field, there will be a force acting on the conductor. The direction of this force can be found using Fleming's Left Hand Rule (also known as 'Flemings left-hand rule for motors').

Similarly if a conductor is forcefully brought under a magnetic field, there will be an induced current in that conductor. The direction of this force can be found using Fleming's Right Hand

Rule.

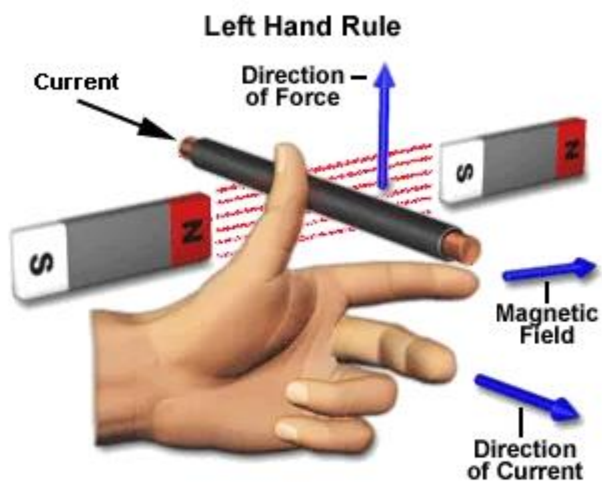
In both Fleming's left and right hand rules, there is a relation between the magnetic field, the current and force. This relation is directionally determined by **Fleming's Left Hand rule** and **Fleming's Right Hand rule** respectively.

These rules do not determine the magnitude but instead show the direction of any of the three parameters (magnetic field, current, force) when the direction of the other two parameters is known.

Fleming's Left-Hand rule is mainly applicable to electric motors and **Fleming's Right-Hand rule** is mainly applicable to electric generators.

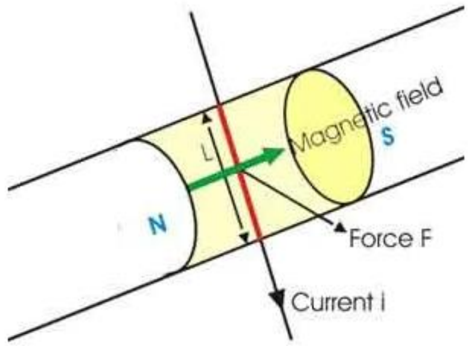
Fleming's Left Hand Rule

It is found that whenever a current carrying conductor is placed inside a magnetic field, a force acts on the conductor, in a direction perpendicular to both the directions of the current and the magnetic field.



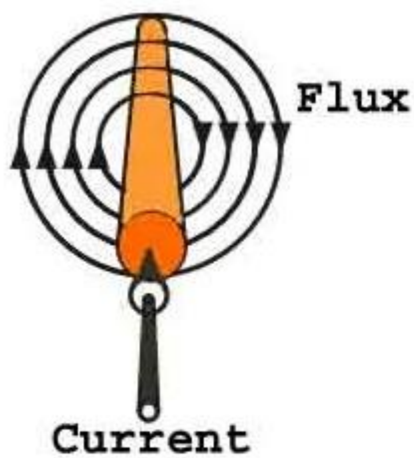
In the figure below, a portion of a conductor of length 'L' is placed vertically in a uniform horizontal magnetic field of strength 'H', produced by two magnetic poles N and S. If the current 'I' is flowing through this conductor, the magnitude of the force acting on the conductor is:

$$F = BiL$$



Hold out your left hand with the forefinger, second finger and thumb at the right angle to one another. If the forefinger represents the direction of the field and the second finger represents that of the current, then thumb gives the direction of the force.

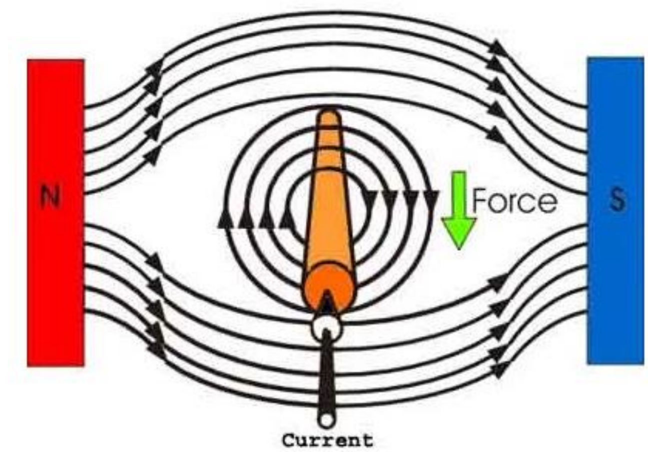
While current flows through a conductor, one magnetic field is induced around it. The magnetic field can be imagined by considering numbers of closed magnetic lines of force around the conductor. The direction of magnetic lines of force can be determined by Maxwell's corkscrew rule or right-hand grip rule. As per these rules, the direction of the magnetic lines of force (or flux lines) is clockwise if the current is flowing away from the viewer, that is if the direction of current through the conductor is inward from the reference plane as shown in the figure.



Now if a horizontal magnetic field is applied externally to the conductor, these two magnetic fields i.e. field around the conductor due to the current through it and the externally applied field will interact with each other. We observe in the picture that the magnetic lines of force of external magnetic field are from N to S pole that is from left to right.

The magnetic lines of force of external magnetic field and magnetic lines of force due to the current in the conductor are in the same direction above the conductor, and they are in the opposite direction below the conductor. Hence there will be larger numbers of co-directional magnetic lines of force above the conductor than that of below the conductor.

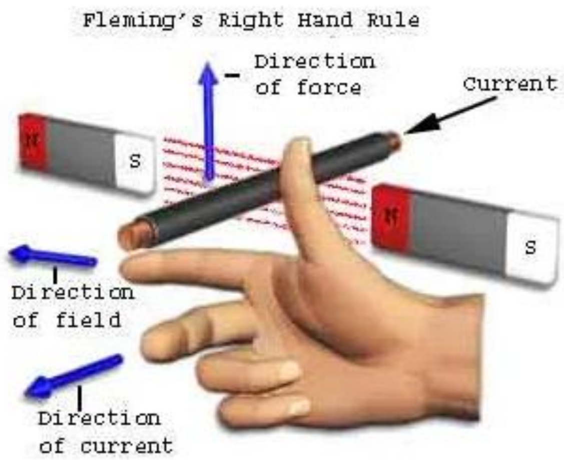
Consequently, there will be a larger concentration of magnetic lines of force in a small space above the conductor. As magnetic lines of force are no longer straight lines, they are under tension like stretched rubber bands.



As a result, there will be a force which will tend to move the conductor from the more concentrated magnetic field to less concentrated magnetic field, that is from the present position to downwards. Now if you observe the direction of the current, force and magnetic field in the above explanation, you will find that the directions are according to the Fleming left-hand rule.

Fleming Right Hand Rule

As per Faraday's law of electromagnetic induction, whenever a conductor moves inside a magnetic field, there will be an induced current in it. If this conductor gets forcefully moved inside the magnetic field, there will be a relation between the direction of applied force, magnetic field and the current. This relation among these three directions is determined by **Fleming's right-hand Rule**.

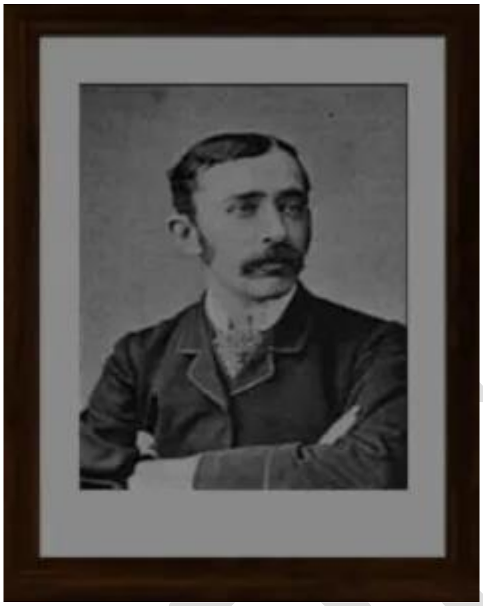


This rule states "Hold out the right hand with the first finger, second finger and thumb at the right angle to each other. If forefinger represents the direction of the line of force, the thumb points in the direction of motion or applied force, then second finger points in the direction of the induced current".

Who Invented The Left and Right Hand Thumb Rules?

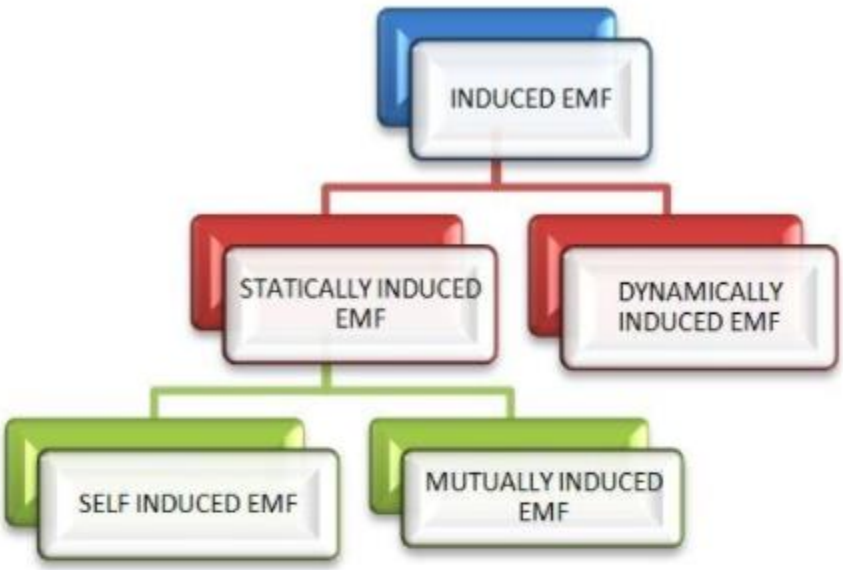
The left and right hand thumb rules were founded by John Ambrose Fleming in the late 19^{th} century.

John discovered both of these rules and named them after himself. The rules are now well known as Fleming's left and right-hand rule.



STATICALLY INDUCED AND DYNAMICALLY INDUCED EMF

Induced e.m.f can be either dynamically induced emf or statically induced emf. in this first case, usually the field is stationary and conductors cut across it (as in d.c. generator). But in the second case, usually the conductor or the coil remains stationary and flux linked with it is changed by simply increasing or decreasing the current producing this flux (as in transformers).



Let the flux linking with the coil of turns N be changed by an amount $d\phi$ in short time dt.

EMF induced, e = Rate of change of flush linkage

= Number of turns × rate of change of flux

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

A minus sign is required to be placed before the right hand side quantity of above expression just to indicate the phenomenon explained by Lenz's law, therefore, expression for induced emf may be written as

$$e = -N\frac{d\phi}{dt} volts \quad \ldots\ldots(1)$$

DYNAMICALLY INDUCED EMF

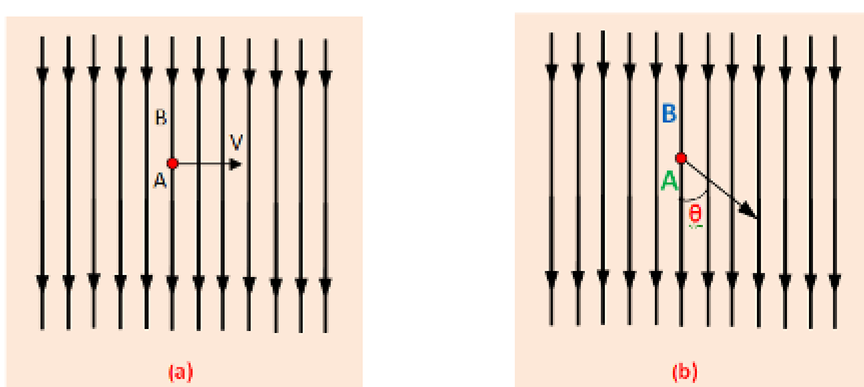
We have learnt that when the flux linking with the coil or circuit changes, an emf is induced in the coil or circuit.

EMF can be induced by changing the flux linking in two ways:

1. By increasing or decreasing the magnitude of the current producing the linking flux. In this case, there is no motion of the conductor or of coil relative to the field and, therefore, emf induced in this way is known as statically induced
2. By moving a conductor in a uniform magnetic field and emf produced in this way is known as *dynamically induced emf*

Consider a conductor of length *l* meters placed in a uniform magnetic field of density $B\frac{Wb}{m^2}$, as shown in Fig.

t



Let, 'l'= Length of the conductor lying within the field. And it moves a distance dx in time dt, So, the area swept by the conductor is =ldx. Hence, flux cut by the conductor = l.dx X B, Change in Flux = B.l.dx weber, Time= dt second

According to Faraday's laws. The e.m.f induced in the conductor . And this induced e.m.f is known as dynamically induced e.m.f.

The rate of change of flux linkages $= \frac{Bldx}{dt} = Bl\frac{dx}{dt} = Blv$ volt [Where, $\frac{dx}{dt}$ is velocity]

If the conductor (A) moves at an angle θ with the direction of flux which is shown in (b).

Then the induced e.m.f is , $e = Blv\sin\theta$ volts $= \vec{lv} \times \vec{B}$
(i.e as cross product vector $\vec{V}$ and $\vec{B}$).

An example, the generator works on the production of dynamically induced e.m.f in the conductors.

The magnitude of emf induced. is proportional to the component of the velocity in a direction perpendicular to the direction of the magnetic field and induced emf is given by

$$e = Blv\sin\theta volts$$

The direction of this induced emf is given by Fleming's right hand rule.

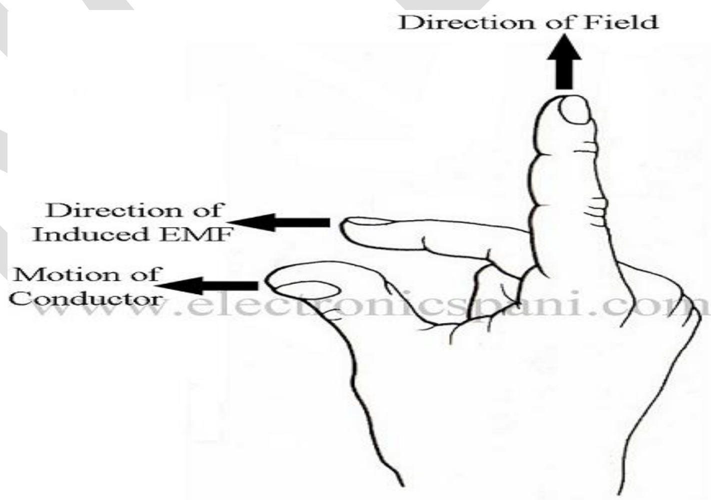


Figure : Fleming's Right Hand Rule

If the thumb, forefinger and middle finger of right hand are held mutually perpendicular to each other, forefinger pointing into the direction of the field and thumb in the direction of motion of conductor then the middle finger will point in the direction of the induced emf as shown in Fig.

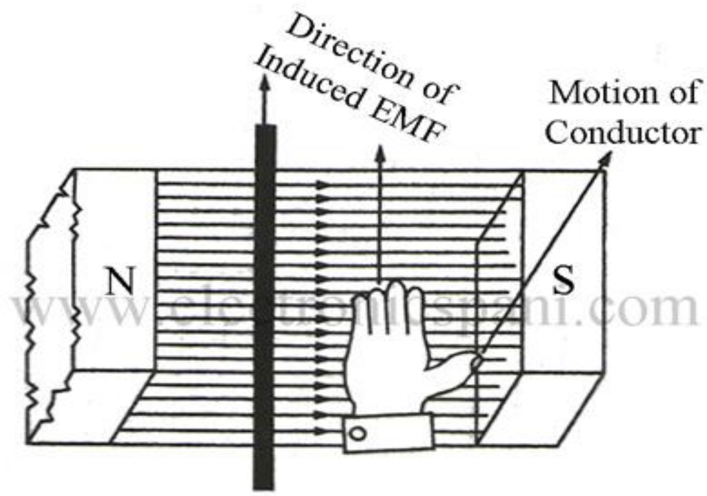


Figure Right Hand Flat Palm Rule

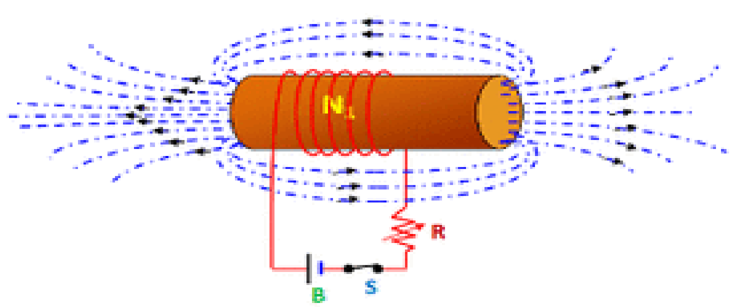
STATICALLY INDUCED E.M.F:-

Statically induced e.m.f is two types which are –

i) Mutually-induced e.m.f.

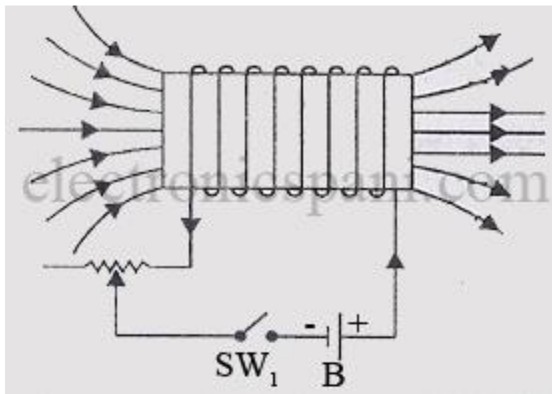
ii) Self-induced e.m.f.

SELF-INDUCED E.M.F:



Self-induced e.m.f is the e.m.f which is produced in the coil due to the change of its own flux linked with it. If the current of the coil is changed, then the flux linked with its own turns will also change which will produce an e.m.f that is called self-induced e.m.f.

Since according to Lenz's law, an induced emf acts to oppose the change that produces it, a self-induced emf is always in such a direction as to oppose the change of current in the coil or circuit in which it is induced. This property of the coil or circuit due to which it opposes any change of the current in the coil or circuit, is known as self-inductance.



Consider a Solenoid of N turns, length *l* meters, area of X-section a square meters and of relative permeability μ_r When the solenoid carries a current of *i* amperes, a magnetic field of flux $\frac{\frac{Ni}{l}}{\mu_0\mu_r a}$ webers is set up around the solenoid and links with it.

If the current flowing through the solenoid is changed, the flux produced by it will change and, therefore, an emf will be induced.

self-induced emf, $$e = -N\frac{d\phi}{dt} = -N\frac{d}{dt}\left[\frac{\frac{Ni}{l}}{\mu_0\mu_r a}\right]$$

$$= -N\frac{\frac{N}{l}}{\mu_0\mu_r a}\frac{di}{dt}$$

$$= -\frac{N^2\mu_r\mu_0 a}{l} \times \frac{di}{dt} \quad \text{……..(2)}$$

The quantity $\frac{N^2\mu_r\mu_0 a}{l}$ is a constant for any given coil or circuit and is called coefficient of self-inductance. It is represented by symbol L and is measured in Henries.

Hence self-induced emf, $e = -L\frac{di}{dt}$

Where $L = \frac{N^2\mu_r\mu_0 a}{l} henrys$

Coefficient of Self Induction

The coefficient of self-induction (L) can be determined from any one of the following three relations.

First Method. In case the dimensions of the solenoid are given, the coefficient of self-induction may be determined from the relation

$$L = \frac{N^2\mu_r\mu_0 a}{l} henrys \qquad ......(3)$$

Second Method. In case the magnitude of induced emf in a coil for a given rate of change of current in the coil is known, self-inductance of the coil may be determined from the following relation.

$$e = L\frac{di}{dt}$$

$$L = \frac{e}{\frac{di}{dt}} \qquad ....(4)$$

Third Method. In case the number of turns of the coil and flux produced per ampere of current in the coil is known, the self-inductance of the coil may be determined from the following relation

$$L = \frac{N\phi}{i} \qquad .....(5)$$

The above relation can be derived as follows:

Magnetic flux produced in a coil of N turns, length *l* meters, area of x-section *a* meters^2 and relative permeability μ_r when carrying a current of I amperes is given by

$$\phi = \frac{\frac{Ni}{l}}{\mu_r \mu_0 a} i$$

and self-inductance of the coil

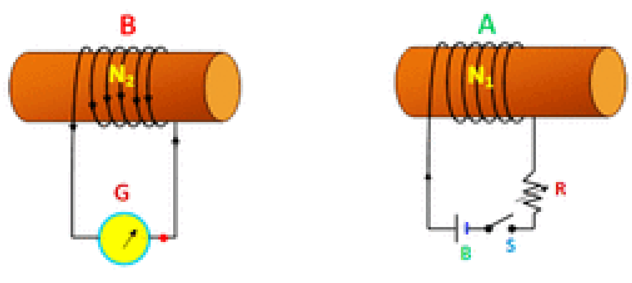
$$L = \frac{N^2 \mu_r \mu_0 a}{l} = \frac{N}{i} \frac{N \mu_r \mu_0 a}{l} i = \frac{N\phi}{i}$$

From the above relation, it is obvious that the self-inductance of a coil or circuit is equal to weber-turns per ampere in the coil or circuit.

In the above relation if $N\phi$=1Wb-turn and i = 1 A then L = 1 H.

Hence a coil is said to have a self-inductance of one henry if a current of 1 A, when flowing through it, produces flux linkage of I Wb-turn in it.

MUTUALLY INDUCED E.M.F:-



Mutually induced e.m.f occurs in between two coils. Let, A & B are two coils which are placed close to each other. If coil A is joined to a battery a switch and a variable resistance R and coil B is connected to a sensitive voltmeter G. When the switch S is closed , a current will flow through the coil A and produce a magnetic field in which partly links with the coil B. As current through A is changed, the flux linked with B is also changed. According to Faraday's law, induced e.m.f is produced in the coil B and This e.m.f know as mutually induce e.m.f.

In the above example, there is no movement of any conductor, the flux variation being brought about by variation in current strength Only. Such an e.m.f induced in one coil by influence of the other coil is called mutually induced e.m.f.

Hence whenever the current in coil A changes, the flux linking with coil B changes and an emf, known as mutually induced emf is induced in coil B.

Consider coil A of turns N_1 wound on a core of length *l* meters, area of cross-section *a* square meters and relative permeability μ_r. When the current of i_1 amperes flows through it, a flux of $\frac{\frac{N_1 i_1}{l}}{\mu_0 \mu_r a}$ is set up around the coil A.

Mutually induced emf, e_m = -Rate of change of flux linkage of coil B

= $-N_2 \times$ rate of change of flux in coil A

$$= -N \frac{d}{dt}\left[\frac{\frac{N_1 i_1}{l}}{\mu_0 \mu_r a}\right]$$

$$= -N \frac{N_1 N_2 a \mu_0 \mu_r}{l} \frac{di_1}{dt} \quad .....(6)$$

The quantity $\frac{N_1 N_2 a \mu_0 \mu_r}{l}$ is called the coefficient of mutual induction of coil B with respect to coil A. It is represented by symbol M and is measured in henrys.

Hence mutually induced emf,

$$e_m = -M \frac{di_1}{dt}$$

Where $M = \frac{N_1 N_2 a \mu_0 \mu_r}{l} henrys$

Coefficient of Mutual Induction

Mutual inductance may be defined as the ability of one coil or circuit to induce an emf in a nearby coil by induction when the current flowing in the first coil is changed. The action is also reciprocal i.e. the change in current flowing through second coil will also induce an emf in the first coil. The ability of reciprocal induction is measured in terms of the coefficient of mutual induction M.

The coefficient of mutual induction (M) can be determined from any one of the following three relations.

First Method. In case the dimensions of the coils are given, the coefficient of mutual induction may be determined from the relation

$$L = \frac{N_1 N_2 a \mu_0 \mu_r}{l} henrys \quad .....(7)$$

Second Method. In case the magnitude of induced emf in the second coil for a given rate of change of current in the first coil is known, mutual inductance between the coil may be determined from the following relation

$$e_m = M \frac{di_1}{dt}$$

Or $$M = \frac{e_m}{\frac{di_1}{dt}} \quad .....(8)$$

Third Method. In case the number of turns of the coil and flux linking with this coil per ampere of current in another coil is known, the mutual inductance of the coil may be determined from the following relation

$$M = N_2 \frac{\phi_2}{l_1} Henry \quad ......(9)$$

EXAMPLE PROBLEMS

1. A solenoid of 500 turns is wound on an iron core of relative permeability 800. The length and radius of the solenoid are 40 cm and 3 cm respectively. Calculate the average emf induced in the solenoid if the current in it changes from 0 to 3 A in 0.4 second.

Solution

N = 500 turns; μr = 800 ;

l = 40 cm = 0.4 m; r = 3 cm = 0.03 m;

di = 3 – 0 = 3 A; dt = 0.4 s

Self inductance,

$$L = \mu n^2 Al \quad \left(\because \mu = \mu_o \mu_r ; A = \pi r^2 ; n = \frac{N}{l}\right)$$

$$= \frac{\mu_o \mu_r N^2 \pi r^2}{l}$$

$$= \frac{4 \times 3.14 \times 10^{-7} \times 800 \times 500^2 \times 3.14 \times \left(3 \times 10^{-2}\right)^2}{0.4}$$

L = 1.77 H

Magnitude of induced emf, $\varepsilon = L\frac{di}{dt}$

$$= \frac{1.77 \times 3}{0.4}$$

$$\varepsilon = 13.275 V$$

2. The self-inductance of an air-core solenoid is 4.8 mH. If its core is replaced by iron core, then its self-inductance becomes 1.8 H. Find out the relative permeability of iron.

Solution

$$L_{air} = 4.8 \times 10^{-3} H$$

$$L_{iron} = 1.8 H$$

$$L_{air} = \mu_o n^2 Al = 4.8 \times 10^{-3} H$$

$$L_{iron} = \mu n^2 Al = \mu_o \mu_r n^2 Al = 1.8 H$$

$$\therefore \mu_r = \frac{L_{iron}}{L_{air}} = \frac{1.8}{4.8 \times 10^{-3}} = 375$$

3. The current flowing in the first coil changes from 2 A to 10 A in 0.4 sec. Find the mutual inductance between two coils if an emf of 60 mV is induced in the second coil. Also determine the induced emf in the second coil if the current in the first coil is changed from 4 A to 16 A in

0.03 sec. Consider only the magnitude of induced emf.

Solution

Case (i):

*di*1 = 10 – 2 = 8 A; d*t* = 0.4 s;

ε2 = 60 ×10−3V

Case (ii):

di1 = 16 – 4 = 12 A;

dt = 0.03 s

(i) Mutual inductance of the second coil with respect to the first coil

$$M_{21} = \frac{\varepsilon_2}{di_1/dt}$$

$$= \frac{60\times10^{-3}\times0.4}{8}$$

$$M_{21} = 3\times10^{-3}H$$

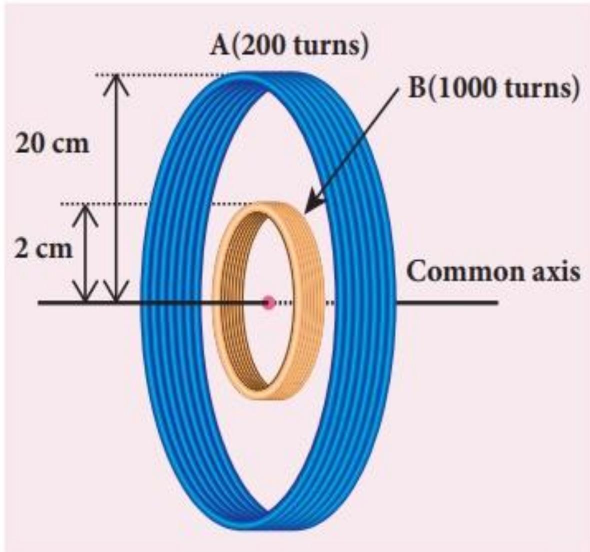
(ii) Induced emf in the second coil due to the rate of change of current in the first coil is

$$\varepsilon_2 = M_{21}\frac{di_1}{dt}$$

$$= \frac{3\times10^{-3}\times12}{0.03}$$

$$\varepsilon_2 = 1.2V$$

4. Consider two coplanar, co-axial circular coils A and B as shown in figure. The radius of coil A is 20 cm while that of coil B is 2 cm. The number of turns is 200 and 1000 for coils A and B respectively. Calculate the mutual inductance of coil B with respect to coil A. If the current in coil A changes from 2 A to 6 A in 0.04 sec, determine the induced emf in coil B and the rate of change of flux through the coil B at that instant.



Solution

NA = 200 turns; NB = 1000 turns;

rA = 20 × 10-2 m; rB = 2 × 10-2 m;

dt = 0.04 s; diA = 6−2 = 4A

Let iA be the current flowing in coil A, then the magnetic field BA at the centre of the circular coil A is

$$B_A = \frac{\mu_\circ N_A i_A}{2r_A} = \frac{4\pi \times 10^{-7} N_A i_A}{2r_A}$$

$$= \frac{10^{-7} \times 2 \times 3.14 \times 200}{20 \times 10^{-2}} \times i_A$$

$$= 6.28 \times 10^{-4} i_A \ \ Wbm^{-2}$$

The magnetic flux linkage of coil B is

$$N_B \Phi_B = N_B B_A A_B$$

$$= 1000 \times 6.28 \times 10^{-4} \times i_A \times 3.14 \times \left(2 \times 10^{-2}\right)^2$$

$$= 7.89 \times 10^{-4} i_A \ \ Wb\ turns$$

The mutual inductance of the coil B with respect to coil A is

$$M_{BA} = \frac{N_B \Phi_B}{i_A} = 7.89 \times 10^{-4} H$$

Induced emf in coil B is

$$\varepsilon_B = -M_{BA} \frac{di_A}{dt}$$

Considering only the magnitude,

$$\varepsilon_B = \frac{7.89 \times 10^{-4} \times (6-2)}{0.04}$$

$$\varepsilon_B = \frac{7.89 \times 10^{-4} \times (4)}{4 \times 10^{-2}}$$

$$\varepsilon_B = 7.89 \times 10^{-2} V$$

The rate of change of magnetic flux of coil *B* is

$$\frac{d(N_B \Phi_B)}{dt} = \varepsilon_B = 78.9\ mWb s^{-1}$$

The rate of change of magnetic flux of coil is

$$\frac{d(N_B \Phi_B)}{dt} = \varepsilon_B = 78.9\ mWb s^{-1}$$

ALTERNATIVE CURRENT FUNDAMENTALS

INTRODUCTION

An electrical circuit is a complete conductive path through which electrons flow from the source to the load and back to the source. The direction and magnitude of the electrons flow however depend on the kind of source. In **Electrical Engineering**, there are basically two types of voltage or current (Electrical Energy) source which defines the kind of circuit and they are; **Alternating Current (or voltage) and Direct Current**.

For the next couple of posts, we will be focusing on the Alternating current, and move through topics ranging from **what is Alternating current** to **AC wave forms** and so on.

AC Circuits

AC circuits as the name (Alternating Current) implies are simply circuits powered by an Alternating Source, either voltage or current. An **Alternating Current or Voltage**, is one in which the value of either the voltage or the current varies about a particular mean value and reverses direction periodically.

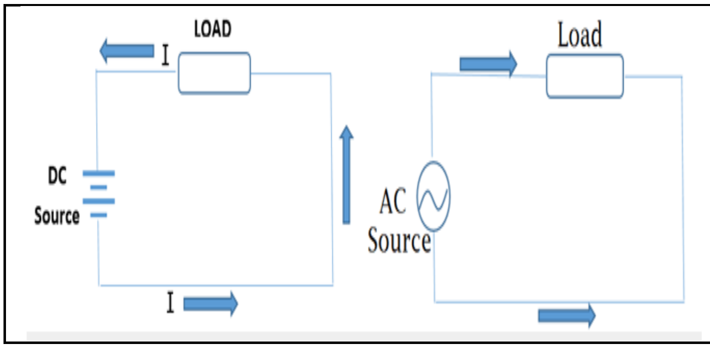
Most present day household and industrial Appliances and systems are powered using alternating current. All DC based plugged in appliances and rechargeable battery based devices technically run on Alternating current as they all use some form of DC power derived from AC for either charging of their batteries or powering of the system. Thus Alternating current is the form via which power is delivered at the mains.

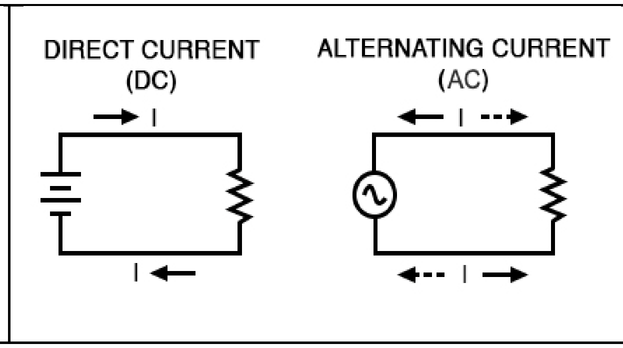
The Alternating circuit came into being in the 1980s when Tesla decided to solve the long range incapability of the Thomas Edison's DC generators. He sought a way of transferring electricity at a high voltage and then employ the use of transformers to step it either up or down as may be needed for distribution and was thus able to minimize power loss across a great distance which was the main problem of Direct Current at the time.

Alternating Current VS Direct Current (AC vs DC)

AC and DC differ in several ways from generation to transmission, and distribution, but for the sake of simplicity, we will keep the comparison to their characteristics for this post.

The major difference between the AC and DC, which is also the cause of their different characteristics, is the direction of flow of electric energy. In DC, Electrons flow steadily in a single direction or forward, while in AC, electrons alternate their direction of flow in periodic intervals. This also leads to alternation in the voltage level as it switches along from positive to negative in line with the current.





Below is a comparison chart to highlight some of the **difference between AC and DC**. Other differences will be highlighted as we go more into exploring Alternating current Circuits.

Comparison Basis	**AC**	**DC**
Energy Transmission Capacity	Travels over long distance with minimal Energy loss	Large amount of energy is lost when sent over long distances
Generation Basics	Rotating a Magnet along a wire.	Steady Magnetism along a wire
Frequency	Usually 50Hz or 60Hz depending on Country	Frequency is Zero
Direction	Reverses direction periodically when flowing through a circuit	It steady constant flow in one direction.
Current	Its Magnitude Vary with time	Constant Magnitude
Source	All forms of AC Generators and Mains	Cells, batteries, Conversion from AC
Passive Parameters	Impedance (RC, RLC, etc)	Resistance Only
Power Factor	Lies between 0&1	Always 1

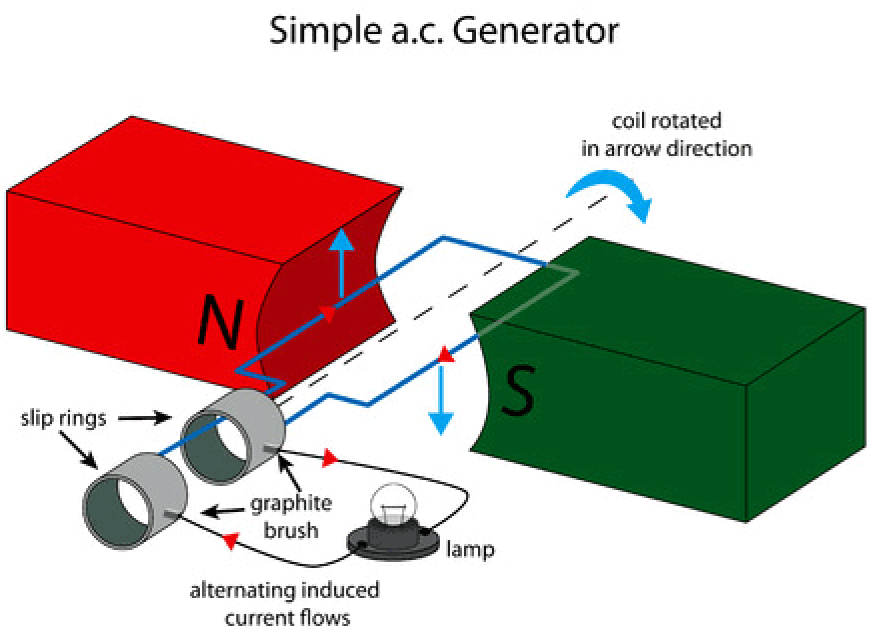
Waveform	Sinusoidal, Trapezoidal, Triangular and Square	Straight line, sometimes Pulsating.

Basic AC Source generation (Single Coil AC Generator)

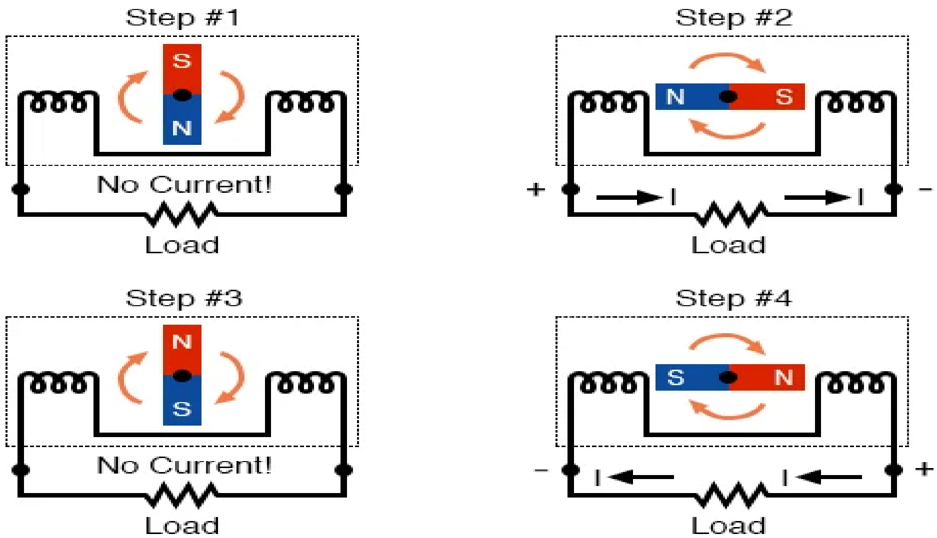
The **principle around AC generation** is simple. If a magnetic field or magnet is rotated along a stationary set of coils (wires) or the rotation of a coil around a stationary magnetic field, an Alternating current is generated using an AC generator(Alternator).

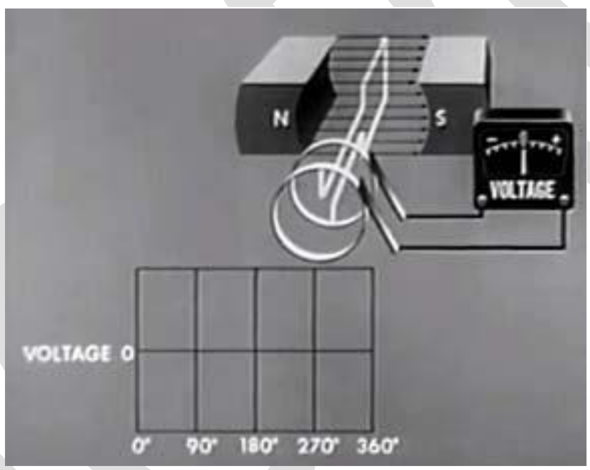
The simplest form of AC generator consists of a loop of wire that is mechanically rotated about an axis while positioned between the north and south poles of a magnet.

Consider the Image below.

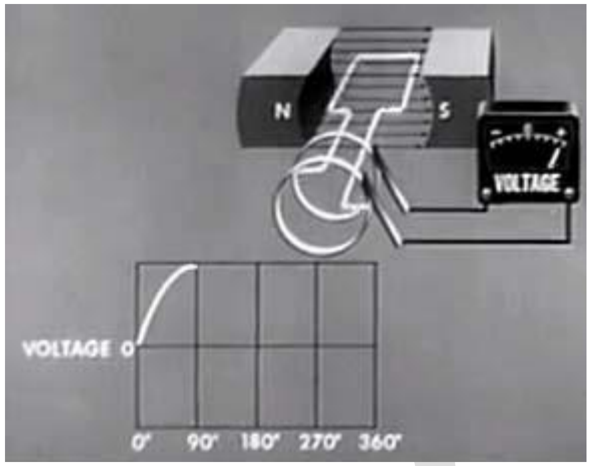


As the armature coil rotates within the magnetic field created by the north and south pole magnets, the magnetic flux through the coil changes, and charges are thus forced through the wire, giving rise to an effective voltage or induced voltage. The magnetic flux through the loop is as a result of the angle of the loop relative to the direction of the magnetic field. Consider the images below;

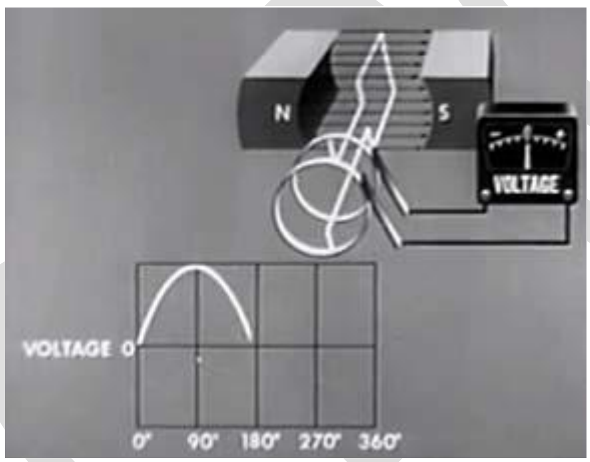




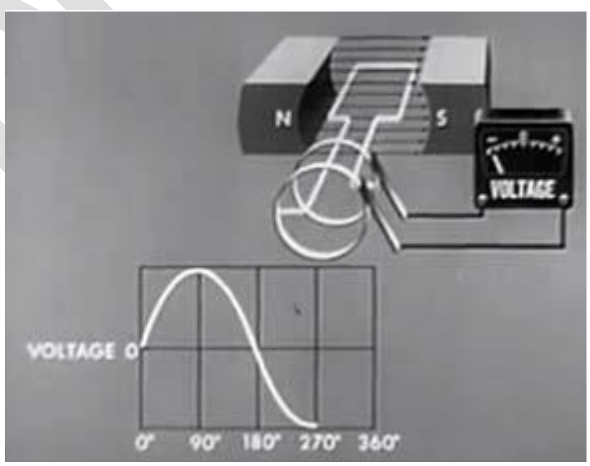
AC generator Armature at 0 degrees



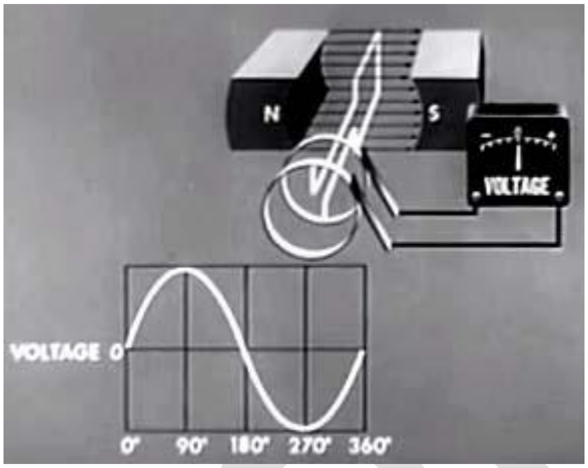
AC generator Armature at 90 degrees



AC generator Armature at 180 degrees



AC generator Armature at 270 degrees



AC generator Armature at 3

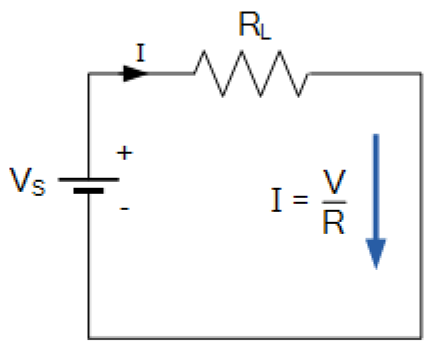
AC WAVEFORMS AND TERMINOLOGIES

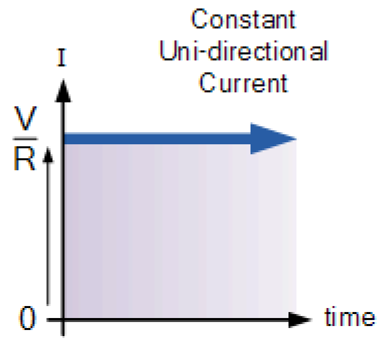
Direct Current or **D.C.** as it is more commonly called, is a form of electrical current or voltage that flows around an electrical circuit in one direction only, making it a "Uni-directional" supply.

Generally, both DC currents and voltages are produced by power supplies, batteries, dynamos and solar cells to name a few. A DC voltage or current has a fixed magnitude (amplitude) and a definite direction associated with it. For example, +12V represents 12 volts in the positive direction, or -5V represents 5 volts in the negative direction.

We also know that DC power supplies do not change their value with regards to time, they are a constant value flowing in a continuous steady state direction. In other words, DC maintains the same value for all times and a constant uni-directional DC supply never changes or becomes negative unless its connections are physically reversed. An example of a simple DC or direct current circuit is shown below.

DC Circuit and Waveform





An alternating function or **AC Waveform** on the other hand is defined as one that varies in both magnitude and direction in more or less an even manner with respect to time making it a “Bi-directional” waveform. An AC function can represent either a power source or a signal source with the shape of an *AC waveform* generally following that of a mathematical sinusoid being defined as: $A(t) = A_{max}*\sin(2\pi f t)$.

The term AC or to give it its full description of Alternating Current, generally refers to a time-varying waveform with the most common of all being called a **Sinusoid** better known as a **Sinusoidal Waveform**. Sinusoidal waveforms are more generally called by their short description as **Sine Waves**. Sine waves are by far one of the most important types of AC waveform used in electrical engineering.

The shape obtained by plotting the instantaneous ordinate values of either voltage or current against time is called an **AC Waveform**. An AC waveform is constantly changing its polarity every half cycle alternating between a positive maximum value and a negative maximum value respectively with regards to time with a common example of this being the domestic mains voltage supply we use in our homes.

This means then that the *AC Waveform* is a “time-dependent signal” with the most common type of time-dependant signal being that of the **Periodic Waveform**. The periodic or AC waveform is the resulting product of a rotating electrical generator. Generally, the shape of any periodic waveform can be generated using a fundamental frequency and superimposing it with harmonic signals of varying frequencies and amplitudes but that’s for another tutorial.

Alternating voltages and currents can not be stored in batteries or cells like direct current (DC) can, it is much easier and cheaper to generate these quantities using alternators or waveform generators when they are needed. The type and shape of an AC waveform depends upon the generator or device producing them, but all AC waveforms consist of a zero voltage line that divides the waveform into two symmetrical halves. The main characteristics of an **AC Waveform** are defined as:

AC Waveform Characteristics

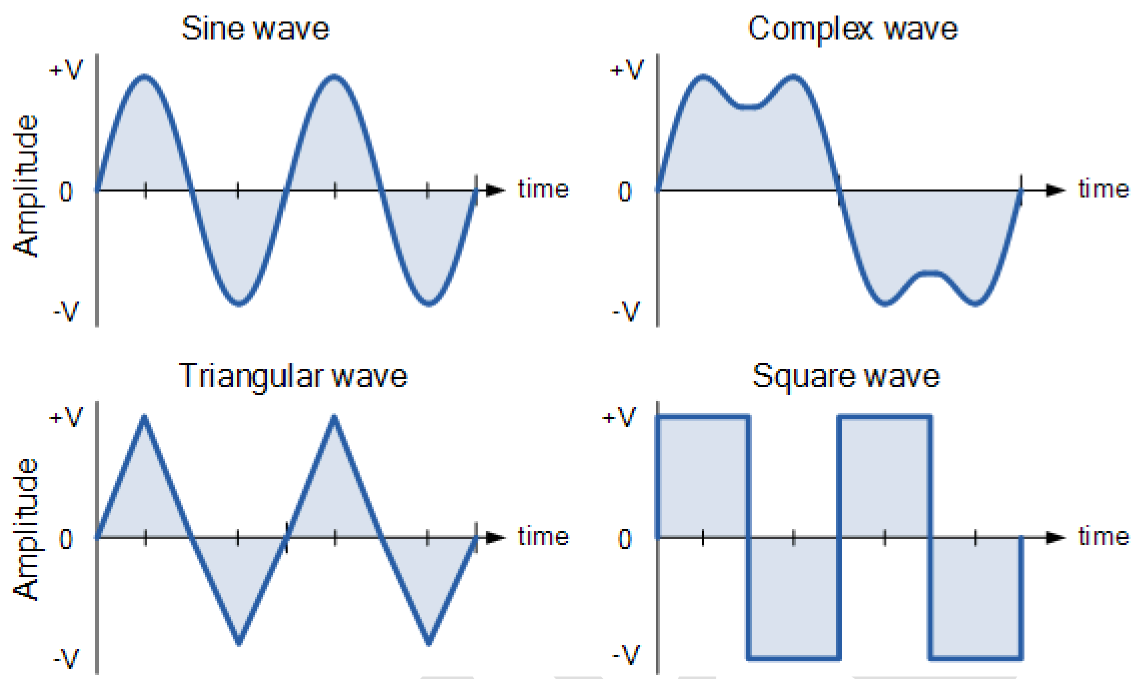
- • The Period, (T) is the length of time in seconds that the waveform takes to repeat itself from start to finish. This can also be called the *Periodic Time* of the waveform for sine waves, or the *Pulse Width* for square waves.
- • The Frequency, (*ƒ*) is the number of times the waveform repeats itself within a one second time period. Frequency is the reciprocal of the time period, ($f = 1/T$) with the unit of frequency being the *Hertz*, (Hz).
- • The Amplitude (A) is the magnitude or intensity of the signal waveform measured in volts or amps.

In our tutorial about **Waveforms** ,we looked at different types of waveforms and said that "**Waveforms** are basically a visual representation of the variation of a voltage or current plotted to a base of time". Generally, for AC waveforms this horizontal base line represents a zero condition of either voltage or current. Any part of an AC type waveform which lies above the horizontal zero axis represents a voltage or current flowing in one direction.

Likewise, any part of the waveform which lies below the horizontal zero axis represents a voltage or current flowing in the opposite direction to the first. Generally for sinusoidal AC waveforms the shape of the waveform above the zero axis is the same as the shape below it. However, for most non-power AC signals including audio waveforms this is not always the case.

The most common periodic signal waveforms that are used in Electrical and Electronic Engineering are the *Sinusoidal Waveforms*. However, an alternating AC waveform may not always take the shape of a smooth shape based around the trigonometric sine or cosine function. AC waveforms can also take the shape of either *Complex Waves*, *Square Waves* or *Triangular Waves* and these are shown below.

Types of Periodic Waveform



The time taken for an **AC Waveform** to complete one full pattern from its positive half to its negative half and back to its zero baseline again is called a **Cycle** and one complete cycle contains both a positive half-cycle and a negative half-cycle. The time taken by the waveform to complete one full cycle is called the **Periodic Time** of the waveform, and is given the symbol "T".

The number of complete cycles that are produced within one second (cycles/second) is called the **Frequency**, symbol *ƒ* of the alternating waveform. Frequency is measured in **Hertz**, (Hz) named after the German physicist Heinrich Hertz.

Then we can see that a relationship exists between cycles (oscillations), periodic time and frequency (cycles per second), so if there are *ƒ* number of cycles in one second, each individual cycle must take 1/*ƒ* seconds to complete.

Relationship Between Frequency and Periodic Time

$$\text{Frequency}, (f) = \frac{1}{\text{Periodic Time}} = \frac{1}{T} \ \text{Hertz}$$

or

$$\text{Periodic Time}, (T) = \frac{1}{\text{Frequency}} = \frac{1}{f} \ \text{seconds}$$

AC Waveform Example No1

1. What will be the periodic time of a 50Hz waveform and 2. what is the frequency of an AC waveform that has a periodic time of 10mS.

1).

$$\text{Periodic Time, } (T) = \frac{1}{f} = \frac{1}{50} = 0.02\text{secs or } 20\text{ms}$$

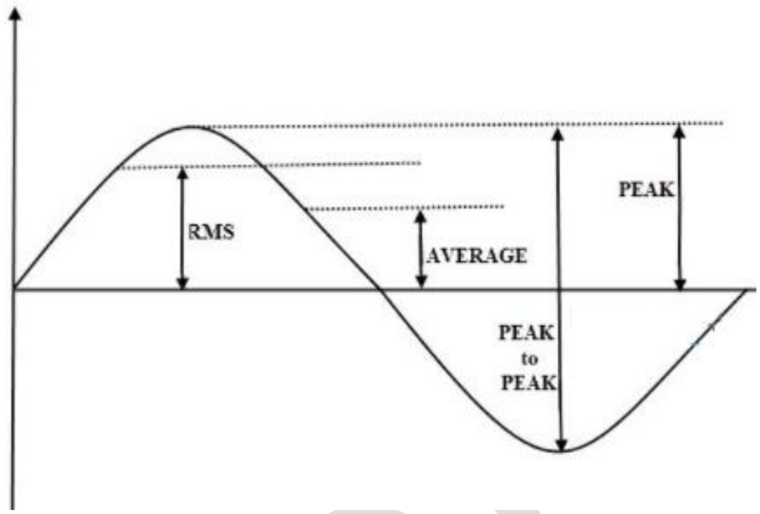
2).

$$\text{Frequency, } (f) = \frac{1}{T} = \frac{1}{10 \times 10^{-3}} = 100\text{Hz}$$

Frequency used to be expressed in "cycles per second" abbreviated to "cps", but today it is more commonly specified in units called "Hertz". For a domestic mains supply the frequency will be either 50Hz or 60Hz depending upon the country and is fixed by the speed of rotation of the generator. But one hertz is a very small unit so prefixes are used that denote the order of magnitude of the waveform at higher frequencies such as **kHz**, **MHz** and even **GHz**.

Definition of Frequency Prefixes

Prefix	Definition	Written as	Periodic Time
Kilo	Thousand	kHz	1ms
Mega	Million	MHz	1us
Giga	Billion	GHz	1ns
Terra	Trillion	THz	1ps



Amplitude of an AC Waveform

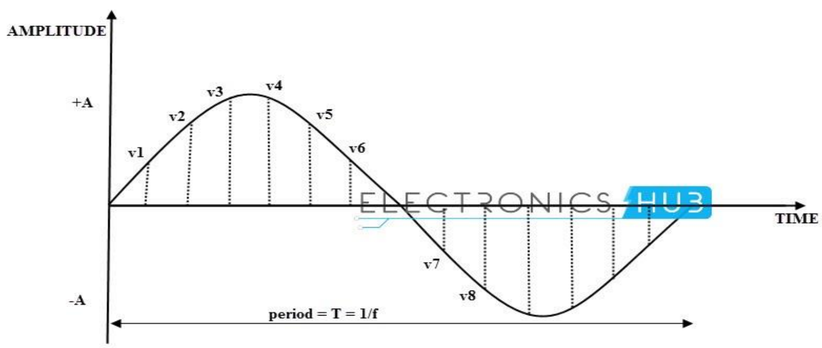
As well as knowing either the periodic time or the frequency of the alternating quantity, another important parameter of the AC waveform is **Amplitude**, better known as its Maximum or Peak value represented by the terms, V*max* for voltage or I*max* for current.

The peak value is the greatest value of either voltage or current that the waveform reaches during each half cycle measured from the zero baseline. Unlike a DC voltage or current which has a steady state that can be measured or calculated using **Ohm's Law**, an alternating quantity is constantly changing its value over time.

For pure sinusoidal waveforms this peak value will always be the same for both half cycles (+Vm = -Vm) but for non-sinusoidal or complex waveforms the maximum peak value can be very different for each half cycle. Sometimes, alternating waveforms are given a *peak-to-peak*, V*p-p* value and this is simply the distance or the sum in voltage between the maximum peak value, +V*max* and the minimum peak value, -V*max* during one complete cycle.

Instantaneous Voltage

Instantaneous voltage is the voltage between two points at a particular moment in time. The voltage of a waveform at a given instant in time is called "Instantaneous voltage".



In the above diagram v1, v2, v3, v4, v5, v6…… are the instantaneous voltages of the sine wave.

To find the instantaneous voltage value of the sine wave, we depend on Maximum voltage of the sine wave.

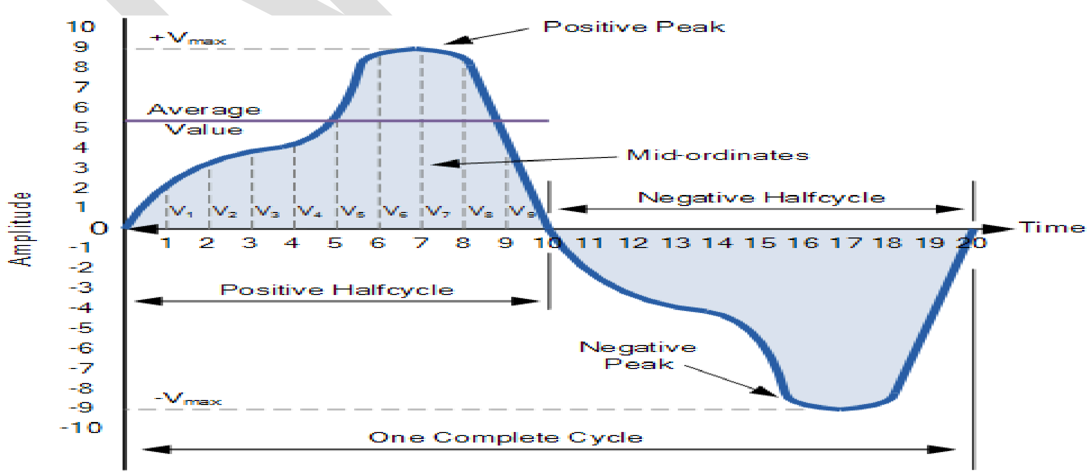
Instantaneous voltage = Maximum voltage x sin θ

Vinst = Vmax x sin θ

The Average Value of an AC Waveform

The average or mean value of a continuous DC voltage will always be equal to its maximum peak value as a DC voltage is constant. This average value will only change if the duty cycle of the DC voltage changes. In a pure sine wave if the average value is calculated over the full cycle, the average value would be equal to zero as the positive and negative halves will cancel each other out. So the average or mean value of an AC waveform is calculated or measured over a half cycle only and this is shown below.

Average Value of a Non-sinusoidal Waveform



To find the average value of the waveform we need to calculate the area underneath the waveform using the mid-ordinate rule, trapezoidal rule or the Simpson's rule found commonly in mathematics. The approximate area under any irregular waveform can easily be found by simply using the mid-ordinate rule.

The zero axis base line is divided up into any number of equal parts and in our simple example above this value was nine, (V_1 to V_9). The more ordinate lines that are drawn the more accurate will be the final average or mean value. The average value will be the addition of all the instantaneous values added together and then divided by the total number. This is given as.

Average Value of an AC Waveform

$$V_{average} = \frac{V_1 + V_2 + V_3 + V_4 + \ldots + V_n}{n}$$

Where: n equals the actual number of mid-ordinates used.

For a pure sinusoidal waveform this average or mean value will always be equal to $0.637*V_{max}$ and this relationship also holds true for average values of current.

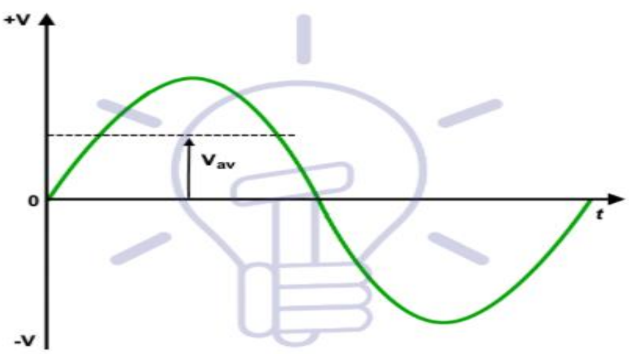
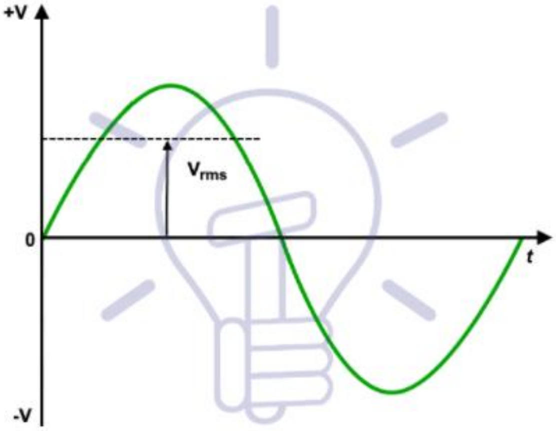


Fig – Average Value of Voltage

The RMS Value of an AC Waveform

The average value of an AC waveform that we calculated above as being: $0.637*V_{max}$ is NOT the same value we would use for a DC supply. This is because unlike a DC supply which is constant and and of a fixed value, an AC waveform is constantly changing over time and has no fixed value. Thus the equivalent value for an alternating current system that provides the same amount of electrical power to a load as a DC equivalent circuit is called the "effective value".

The effective value of a sine wave produces the same I^2*R heating effect in a load as we would expect to see if the same load was fed by a constant DC supply. The effective value of a sine wave is more commonly known as the **Root Mean Squared** or simply **RMS** value as it is calculated as the square root of the mean (average) of the square of the voltage or current.



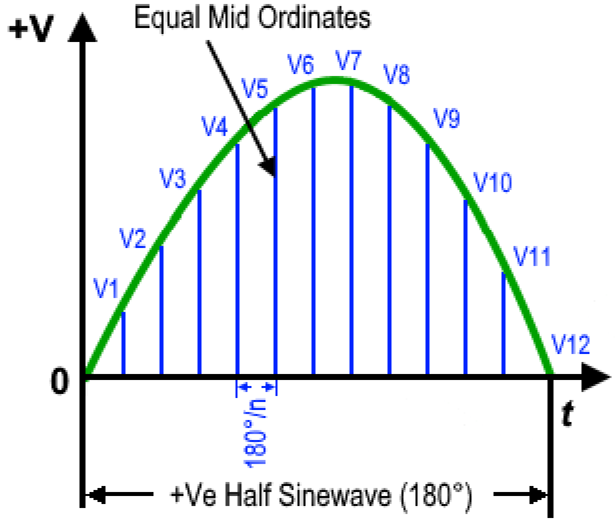
That is V_{rms} or I_{rms} is given as the square root of the average of the sum of all the squared mid-ordinate values of the sine wave. The RMS value for any AC waveform can be found from the following modified average value formula as shown.

RMS Value of an AC Waveform

$$V_{RMS} = \sqrt{\frac{V_1^2 + V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2}{n}}$$

Where: n equals the number of mid-ordinates.

For a pure sinusoidal waveform this effective or R.M.S. value will always be equal too: $1/\sqrt{2}*V_{max}$ which is equal to $0.707*V_{max}$ and this relationship holds true for RMS values of current. The RMS value for a sinusoidal waveform is always greater than the average value except for a rectangular waveform. In this case the heating effect remains constant so the average and the RMS values will be the same.



One final comment about R.M.S. values. Most multimeters, either digital or analogue unless otherwise stated only measure the R.M.S. values of voltage and current and not the average. Therefore when using a multimeter on a direct current system the reading will be equal to I = V/R and for an alternating current system the reading will be equal to Irms = Vrms/R.

Also, except for average power calculations, when calculating RMS or peak voltages, only use V_{RMS} to find I_{RMS} values, or peak voltage, Vp to find peak current, Ip values. Do not mix them together as Average, RMS or Peak values of a sine wave are completely different and your results will definitely be incorrect.

RMS Voltage Value Formulas for Different Wave forms

In the below table, the RMS Voltage Value formulas are shown for different kind of sinusoidal wave forms.

Waveform Type	**Formula for RMS Value (V_{RMS})**
Sine Wave	$V_{PK} / \sqrt{2}$
Half wave rectified sine wave	$V_{PK} / \sqrt{2}$
Full wave rectified sine wave	$V_{PK} / \sqrt{2}$
Square wave	V_{PK}

Triangle waveform	$V_{PK} / \sqrt{3}$
Sawtooth waveform	$V_{PK} / \sqrt{3}$

Form Factor and Crest Factor

Although little used these days, both **Form Factor** and **Crest Factor** can be used to give information about the actual shape of the AC waveform. Form Factor is the ratio between the average value and the RMS value and is given as.

$$\text{Form Factor} = \frac{\text{R.M.S value}}{\text{Average value}} = \frac{0.707 \times V_{max}}{0.637 \times V_{max}}$$

For a pure sinusoidal waveform the Form Factor will always be equal to 1.11. Crest Factor is the ratio between the R.M.S. value and the Peak value of the waveform and is given as.

$$\text{Crest Factor} = \frac{\text{Peak value}}{\text{R.M.S. value}} = \frac{V_{max}}{0.707 \times V_{max}}$$

For a pure sinusoidal waveform the Crest Factor will always be equal to 1.414.

AC Waveform Example No2

A sinusoidal alternating current of 6 amps is flowing through a resistance of 40Ω. Calculate the average voltage and the peak voltage of the supply.

The R.M.S. Voltage value is calculated as:

$$V_{RMS} = I \times R = 6 \times 40 = 240V$$

The Average Voltage value is calculated as:

$$\text{Form Factor} = \frac{V_{RMS}}{V_{average}}$$

$$\therefore\ V_{average} = \frac{V_{RMS}}{\text{Form Factor}} = \frac{240}{1.11} = 216.2\ \text{volts}$$

The Peak Voltage value is calculated as:

$$\text{Peak Voltage} = \text{R.M.S.} \times 1.414$$

$$\therefore\ 240 \times 1.414 = 339.4\ \text{volts}$$

The use and calculation of Average, R.M.S, Form factor and Crest Factor can also be use with any type of periodic waveform including Triangular, Square, Sawtoothed or any other irregular or complex voltage/current waveform shape. Conversion between the various sinusoidal values can sometimes be confusing so the following table gives a convenient way of converting one sine wave value to another.

Sinusoidal Waveform Conversion Table

Convert From	Multiply By	Or By	To Get Value
Peak	2	$(\sqrt{2})^2$	Peak-to-Peak
Peak-to-Peak	0.5	1/2	Peak
Peak	0.707	$1/(\sqrt{2})$	RMS
Peak	0.637	$2/\pi$	Average
Average	1.570	$\pi/2$	Peak
Average	1.111	$\pi/(2\sqrt{2})$	RMS

RMS	1.414	√2	Peak
RMS	0.901	(2√2)/π	Average

Example Problem 3

If a sine wave is defined as Vm¬ = 150 sin (220t), then find its RMS velocity and frequency and instantaneous velocity of the waveform after a 5 ms of time.

Solution:

The general equation for the sine wave is Vt = Vm sin (ωt)

Comparing this to the given equation Vm¬ = 150 sin (220t),

The peak voltage of the maximum voltage is 150 volts and

Angular frequency is 220 rad / sec.

The RMS velocity of the wave form is given as

Vrms = 0.707 x max amplitude or peak value.

= 0.0707 x 150 = 106.05 volts

The angle of a sine wave is a function of its frequency, as we know the sine wave's angular velocity, so we can find out the frequency of the waveform. By using the relation between ω and f

Angular velocity (ω) =

Frequency (f) = ω / 2 π

For the given sine wave form ω = 220,

Frequency = 220 / 2 π

= 220 / (2 x 3.1416)

= 220 / 6.2832

= 35.0140 Hz

The instantaneous value is given by after a time of 5 ms can be calculated by using the below formula.

Vi = 150 sin (220 x 5 ms)

= 150 sin (1.1)

= 150 x 0.019

= 133.68 volts

Phase of the angle at time t = 5 ms are calculated in radians. We can convert the radian values into degree values very simply. The formula for conversion of radians to degrees is

Degrees = (1800/ π)×radians

Converting 1.1 radians into degrees,

= (1800 / π) x 1.1

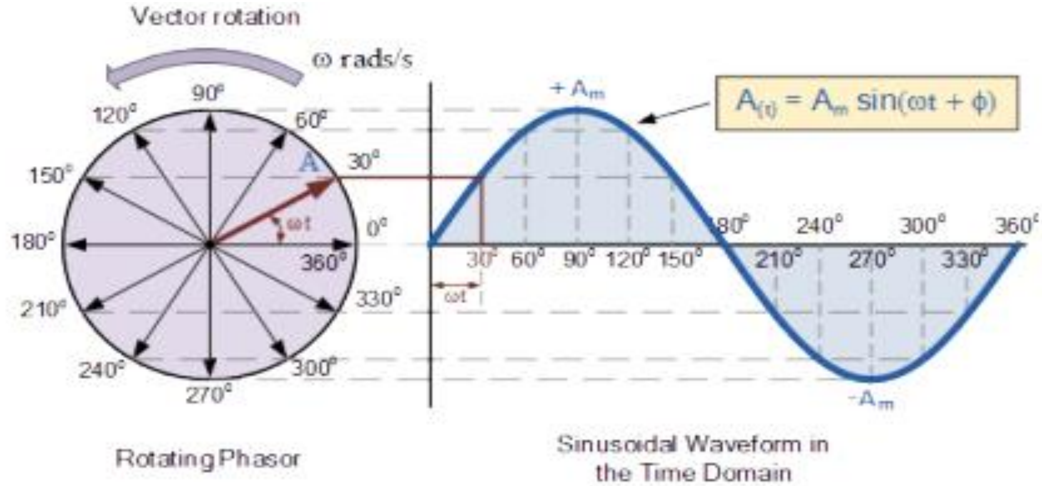
= 63.02 degrees

MODULE III

AC CIRCUITS

SINUSOIDAL REPRESENTATION OF AC

The sinusoidal waveform A (t)=Am .sin(ωt+φ) could be expressed as a vector, rotating anticlockwise with an angular frequency ω



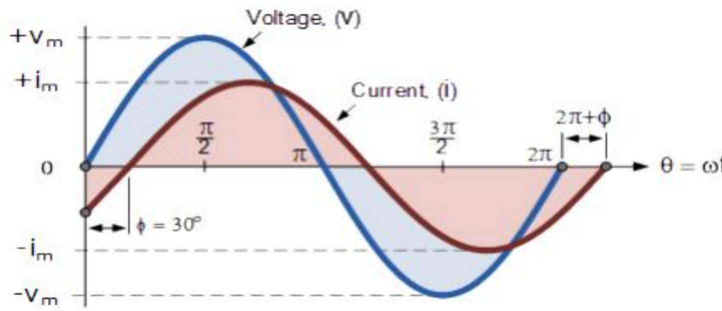
As can be seen when the time is t=0 the vecor is rotated at 0° , 180 ° and 360 ° . Similarly when A (t) has a maximum (+Am) the vector is rotated at 90° and when A (t) has a minimum (−Am) – the vector is rotated at −90° .

Consider the current and voltage of a branch are:

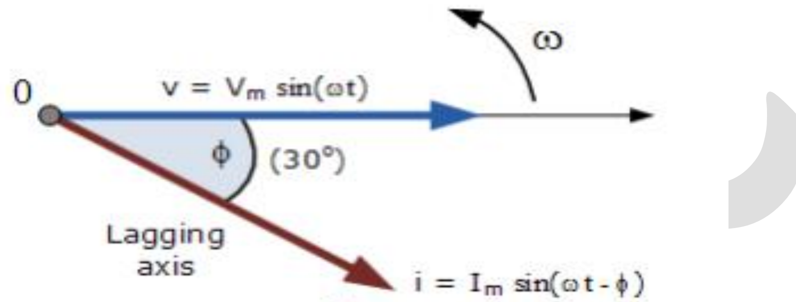
v (t)=V m .sin(ωt)

i(t)=I m .sin (ωt−30°)

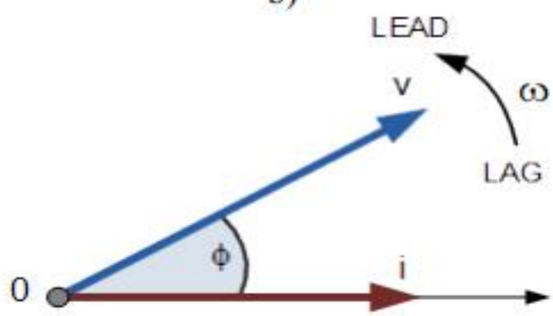
The current lags the voltage by φ=30 ° (fig.). Then the phasor diagram of the two vectors for t=0 is presented in fig. 5.6b. In time the two vectors rotate together with angular frequency ω however the current vector will continue to lag the voltage by 30°



a)



b)



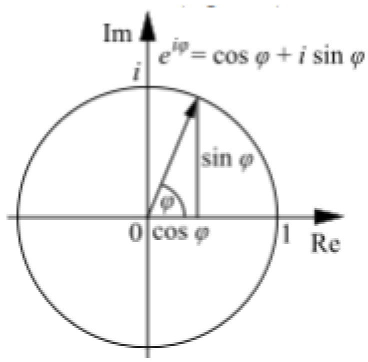
c)

The sinusoidal waveform $A(t)=A_m .\sin(\omega t+\varphi)$ could be expressed in phasor form as:

$\hat{A}_m=A_m . e^{j\varphi}=A_m \cos(\varphi)+ j A_m \sin(\varphi)$

where $\dot{A}_m$ is also called complex amplitude.

The above equation is called the Euler's formula

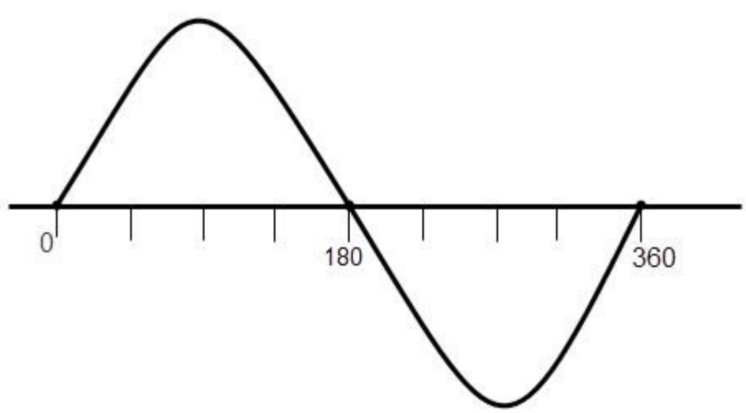


PHASE:

The position of a wave particle of a periodic waveform is known as "Phase" of a waveform. The complete phase of a full cycle of a waveform is 360^0.

When two or more waves of the same frequency are interfering in a medium or made to travel in the same path, then the "phase" of waves play an important role to produce the desired output without any noise occurring in it.

Phase can also be defined as "The relative displacement of two waves with respect to each other".



Phase can be expressed in radians and degrees also. One radian = 57.3 degrees.

PHASE DIFFERENCE

The phase difference of a sine wave can be defined as "The time interval by which a wave leads by or lags by another wave" and the phase difference is not a property of only one wave, it's the relative property to two or more waves. This is also called as “Phase angle” or “Phase offset”.

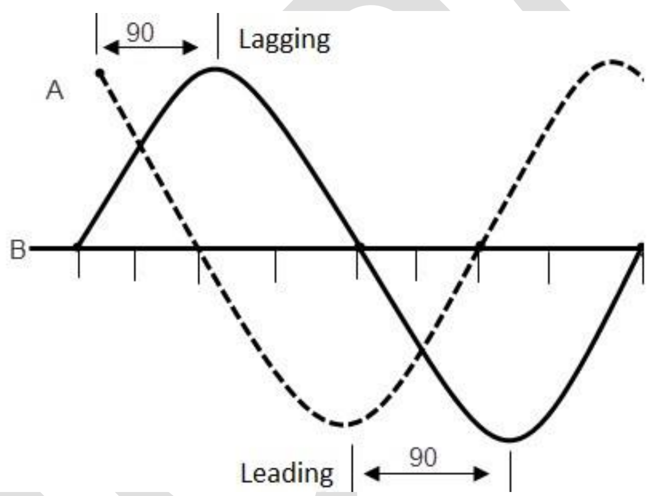
The phase difference represented by the Greek letter Phi (Φ). The complete phase of a waveform can be defined as 2π radians or 360 degrees.

Leading phase means, a waveform is ahead of another wave with the same frequency and Lagging phase means, a waveform is behind another wave with the same frequency.

Phase quadrature: When the phase difference between two waves is 90^0 (it may be = + 90^0 or – 90^0), then the waves are said to be in ‘Phase quadrature’.

Phase opposition: When the phase difference between two waves is 180^0 (it may be = + 180^0 or – 180^0), then the waves are said to be in ‘Phase opposition.

To understand this concept clearly, observe the figure below.



The time interval and phase of a waveform are inversely proportional to each other. It means

t deg = 1 / (360 f) (Degrees)

t rad = 1 / (6.28 f) (Radians)

Where f is the frequency of the waveform and t is the time period.

For example, if two sine waves have the same frequency and have a phase shift of $\pi/2$ radians, then the phases of the waves can be defined as ($n\pi + 1$) and $n\pi$ radians.

The phase shift of the waveforms can be represented in time period (T) also. For example + 6ms and – 7ms etc.

Phase Difference Equation

The phase difference of sine waveforms can be expressed by below given equation, using maximum voltage or amplitude of the wave forms,

$A_{(t)} = A_{max} \times \sin(\omega t \pm Ø)$

Where

Amax is the amplitude of the measures sine wave

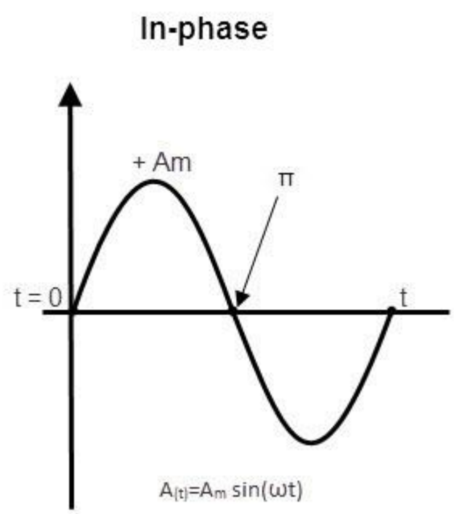
ωt is the angular velocity (radians / Sec)

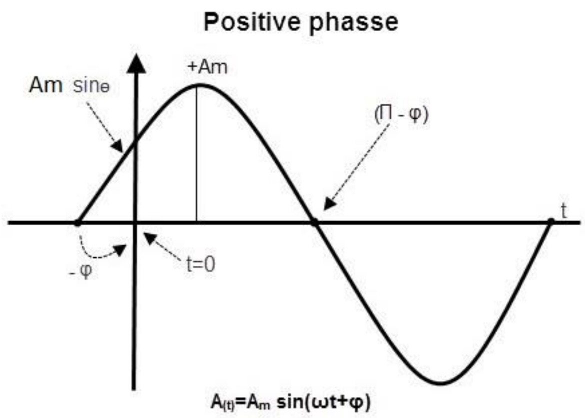
Φ is the phase angle. (Radians or degrees)

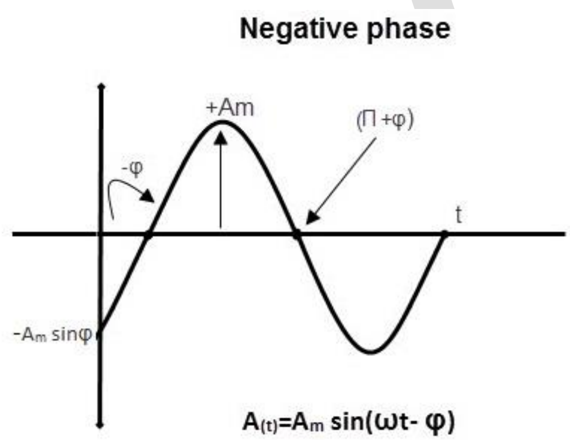
If Φ < 0, then the phase angle of the wave is said to be in negative phase. Similarly, if Φ > 0, then the phase angle of the wave is said to be in a positive phase.

Phase Relationship of a Sinusoidal Waveform

Every alternating waveform will have its current , voltage and frequency. If the voltage and angular velocities of the two waveforms are same, then their phase is also same at any instant of time.





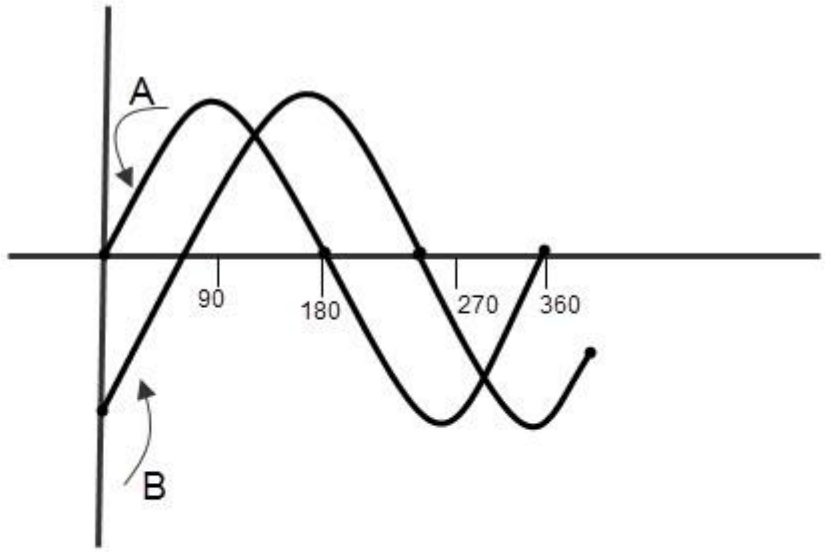


In the above picture, we can see three waves which are starting at the origin of the axis, leading at origin and lagging at the origin of the coordinate axis respectively.

PHASE DIFFERENCE OF WAVEFORMS

Out of Phase

When alternating waveforms have the same frequency but different phase, they are said to be "Out of phase". The phase difference is not zero for out of phased waves. Observe the below figure which describes the out of phase concept of two sine waves. For in phase waveforms, the retardation is fractions of numbers of wavelengths like 1/2, 2/3, 3/5… etc.



In the above picture, the wave 'B' leads by 90^0 ($\Phi = 90^0$) to wave 'A'. So we can say that the two waves are out – of – phase.

For out of phased waves, there are two conditions. They are

1. Leading phase

2. Lagging phase

Leading Phase

When two waveforms of the same frequency are travelling along the same axis and one waveform is ahead of another, then it is called 'Leading phase wave'.

The current and voltage equations for leading phased waveforms are

Voltage (Vt) = Vm sin ωt

Current (it) = Im sin (ωt – Φ)

Where Φ is leading phase angle.

Lagging Phase

When two waveforms of the same frequency are travelling along the same axis and one waveform is behind of another, then it is called 'Lagging phase wave'.

The voltage and current equations for leading phased waveforms are

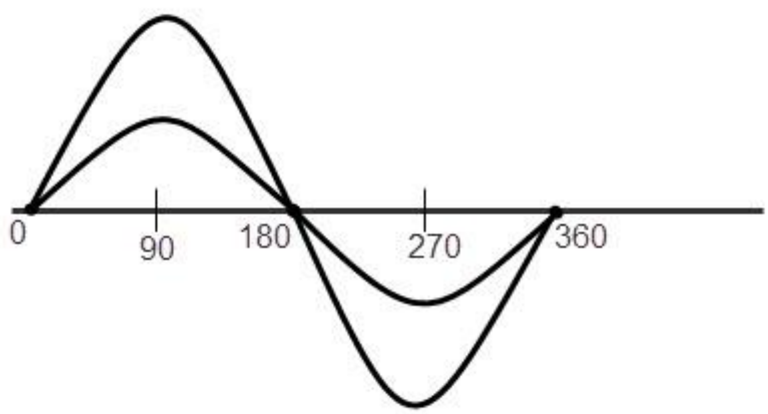
Voltage (Vt) = Vm sin ωt

Current (it) = Im sin (ωt + Φ)

Where Φ is lagging phase angle.

IN Phase Sine Waveforms

When the difference between phase of two alternating waves is zero, the waves are said to be "In-phase". This can be occurred when the two waveforms have the same frequency and the same phase. For in phase waveforms, the retardation is a whole number of wavelengths like 0, 1, 2, 3… The in-phase waveforms are shown in below figure.



The waveforms in the above picture have different amplitude (maximum voltage) but they have the same frequency.

Ex: If two sine waves A & B are out of phase and the phase difference is 25^0 then we can explain the relation between the waves as

Wave 'A' leads by wave 'B' by 25^0 or wave 'B' lags by wave 'A' by 25^0. So the current and voltages of these waveforms also vary with the phase shift of the out of phased waveforms.

Voltage and Current Phase Relationships to R,L,C

The R L C circuit is also called as "Resonance circuit". The voltage and current behavior of the resistor, capacitor and inductors with respect to phase is explained below.

- Resistor: In resistor, the current and the voltage are in the same phase. So the phase difference between them is measured as 0.
- Capacitor: In a capacitor, the current and voltages are not in the same phase and the

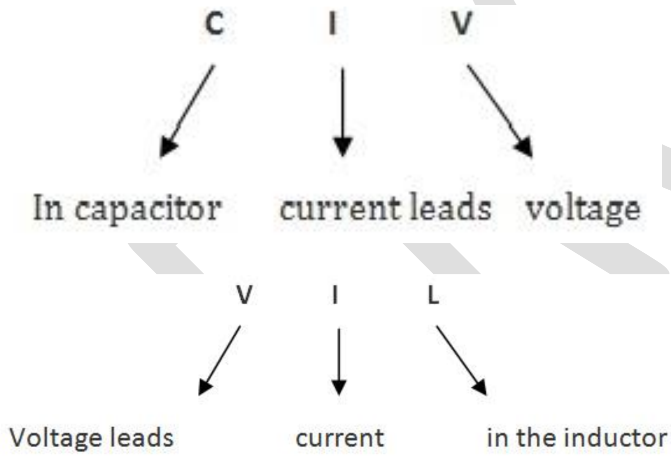
current leads voltage by 90^0. So the phase difference between current and voltage in a capacitor is measured as 90^0.

- Inductor: In inductor also, the current and voltages are not in the same phase. The voltage leads current by 90^0.So the phase difference between voltage and current in capacitor is measured as 90^0. This is exactly opposite to nature of the capacitor.

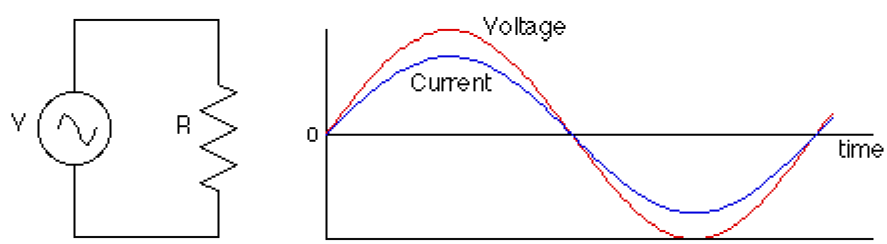
NOTE:

There is a simple technique to remember this voltage, current relationship, without any confusion. That technique is C I V I L

The first 3 letters C I V represents that, in a capacitor, I (current) leads V (voltage).



RESISTANCE IN AN AC CIRCUIT

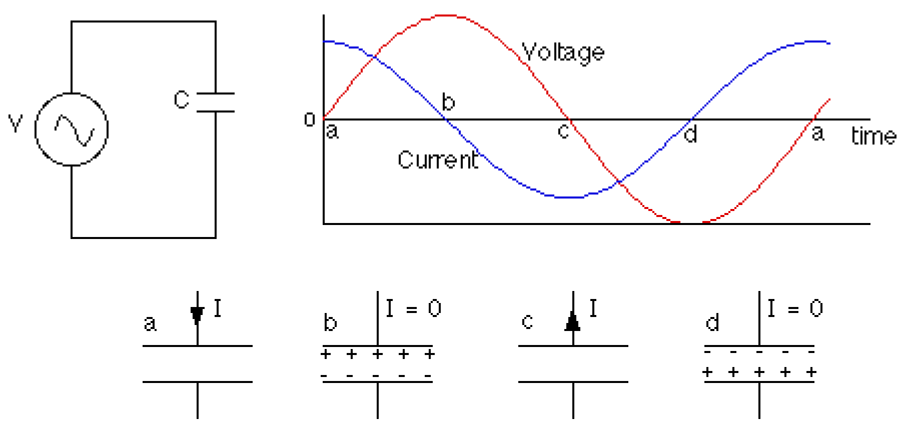


The relationship V = IR applies for resistors in an AC circuit, so

$$I = V / R = (V_0 / R) \sin(\omega t) = I_0 \sin(\omega t)$$

In AC circuits we'll talk a lot about the phase of the current relative to the voltage. In a circuit which only involves resistors, the current and voltage are in phase with each other, which means that the peak voltage is reached at the same instant as peak current. In circuits which have capacitors and inductors (coils) the phase relationships will be quite different.

CAPACITANCE IN AN AC CIRCUIT



Consider now a circuit which has only a capacitor and an AC power source (such as a wall outlet). A capacitor is a device for storing charging. It turns out that there is a 90° phase difference between the current and voltage, with the current reaching its peak 90° (1/4 cycle) before the voltage reaches its peak. Put another way, the current leads the voltage by 90° in a purely capacitive circuit.

To understand why this is, we should review some of the relevant equations, including:

relationship between voltage and charge for a capacitor: $CV = Q$

relationship between current and the flow of charge : $I = \Delta Q / \Delta t$

The AC power supply produces an oscillating voltage. We should follow the circuit through one cycle of the voltage to figure out what happens to the current.

Step 1 - At point a (see diagram) the voltage is zero and the capacitor is uncharged. Initially, the voltage increases quickly. The voltage across the capacitor matches the power supply voltage, so the current is large to build up charge on the capacitor plates. The closer the voltage gets to its peak, the slower it changes, meaning less current has to flow. When the voltage reaches a peak at point b, the capacitor is fully charged and the current is momentarily zero.

Step 2 - After reaching a peak, the voltage starts dropping. The capacitor must discharge now, so the current reverses direction. When the voltage passes through zero at point c, it's changing quite rapidly; to match this voltage the current must be large and negative.

Step 3 - Between points c and d, the voltage is negative. Charge builds up again on the capacitor plates, but the polarity is opposite to what it was in step one. Again the current is negative, and as the voltage reaches its negative peak at point d the current drops to zero.

Step 4 - After point d, the voltage heads toward zero and the capacitor must discharge. When the voltage reaches zero it's gone through a full cycle so it's back to point a again to repeat the cycle.

The larger the capacitance of the capacitor, the more charge has to flow to build up a particular voltage on the plates, and the higher the current will be. The higher the frequency of the voltage, the shorter the time available to change the voltage, so the larger the current has to be. The current, then, increases as the capacitance increases and as the frequency increases.

Usually this is thought of in terms of the effective resistance of the capacitor, which is known as the capacitive reactance, measured in ohms. There is an inverse relationship between current and resistance, so the capacitive reactance is inversely proportional to the capacitance and the frequency:

A capacitor in an AC circuit exhibits a kind of resistance called capacitive reactance, measured in ohms. This depends on the frequency of the AC voltage, and is given by:

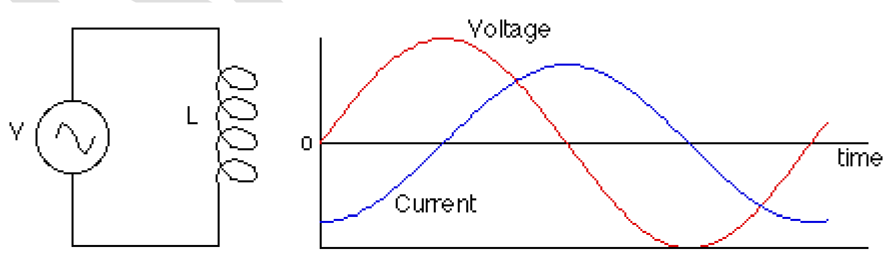
capacitive reactance: $X_C = 1 / \omega C = 1 / 2\pi f C$

We can use this like a resistance (because, really, it is a resistance) in an equation of the form V = IR to get the voltage across the capacitor:

$V = I X_C$

Note that V and I are generally the rms values of the voltage and current.

INDUCTANCE IN AN AC CIRCUIT



An inductor is simply a coil of wire (often wrapped around a piece of ferromagnet). If we now look at a circuit composed only of an inductor and an AC power source, we will again find that there is a 90° phase difference between the voltage and the current in the inductor. This time, however, the current lags the voltage by 90°, so it reaches its peak 1/4 cycle after the voltage peaks.

The reason for this has to do with the law of induction:

$\varepsilon = -N \Delta\Phi / \Delta t$ or $\varepsilon = -L \Delta I / \Delta t$

Applying Kirchoff's loop rule to the circuit above gives:

$V - L \Delta I / \Delta t = 0$ so $V = L \Delta I / \Delta t$

As the voltage from the power source increases from zero, the voltage on the inductor matches it. With the capacitor, the voltage came from the charge stored on the capacitor plates (or, equivalently, from the electric field between the plates). With the inductor, the voltage comes from changing the flux through the coil, or, equivalently, changing the current through the coil, which changes the magnetic field in the coil.

To produce a large positive voltage, a large increase in current is required. When the voltage passes through zero, the current should stop changing just for an instant. When the voltage is large and negative, the current should be decreasing quickly. These conditions can all be satisfied by having the current vary like a negative cosine wave, when the voltage follows a sine wave.

How does the current through the inductor depend on the frequency and the inductance? If the frequency is raised, there is less time to change the voltage. If the time interval is reduced, the change in current is also reduced, so the current is lower. The current is also reduced if the inductance is increased.

As with the capacitor, this is usually put in terms of the effective resistance of the inductor. This effective resistance is known as the inductive reactance. This is given by:

$X_L = \omega L = 2\pi f L$

where L is the inductance of the coil (this depends on the geometry of the coil and whether its got a ferromagnetic core). The unit of inductance is the henry.

As with capacitive reactance, the voltage across the inductor is given by:

$V = IX_L$

Where does the energy go?

One of the main differences between resistors, capacitors, and inductors in AC circuits is in what happens with the electrical energy. With resistors, power is simply dissipated as heat. In a capacitor, no energy is lost because the capacitor alternately stores charge and then gives it back again. In this case, energy is stored in the electric field between the capacitor plates. The amount of energy stored in a capacitor is given by:

energy in a capacitor : Energy = 1/2 CV^2

In other words, there is energy associated with an electric field. In general, the energy density (energy per unit volume) in an electric field with no dielectric is:

Energy density in an electric field = 1/2 $\varepsilon_0 E^2$

With a dielectric, the energy density is multiplied by the dielectric constant.

There is also no energy lost in an inductor, because energy is alternately stored in the magnetic field and then given back to the circuit. The energy stored in an inductor is:

energy in an inductor: Energy = 1/2 LI^2

Again, there is energy associated with the magnetic field. The energy density in a magnetic field is:

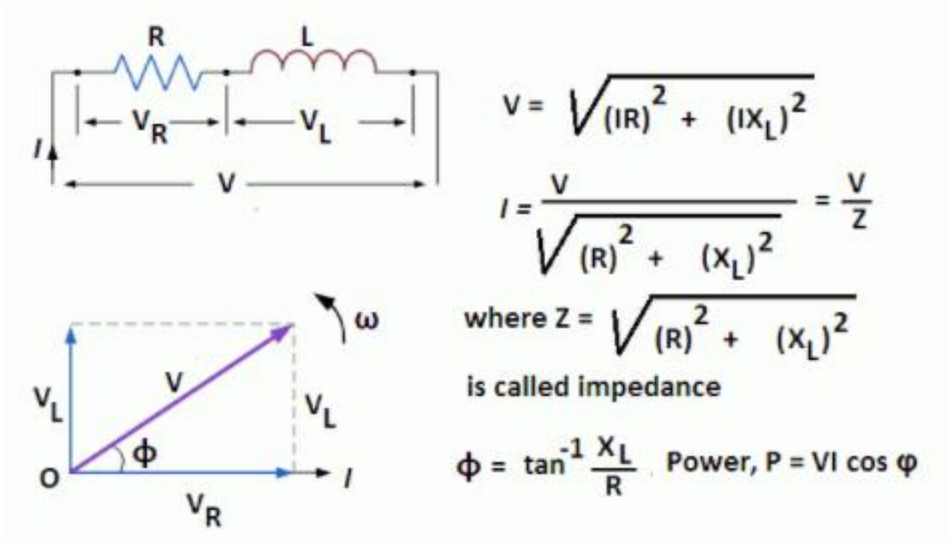
Energy density in a magnetic field = $B^2 / (2 \mu_0)$

RC | RLC | RL Series Circuits

In actual practice, AC circuits contain two or more than two components connected in series. In a series circuit, each component carries the same current. An AC series circuit may be classified as under:

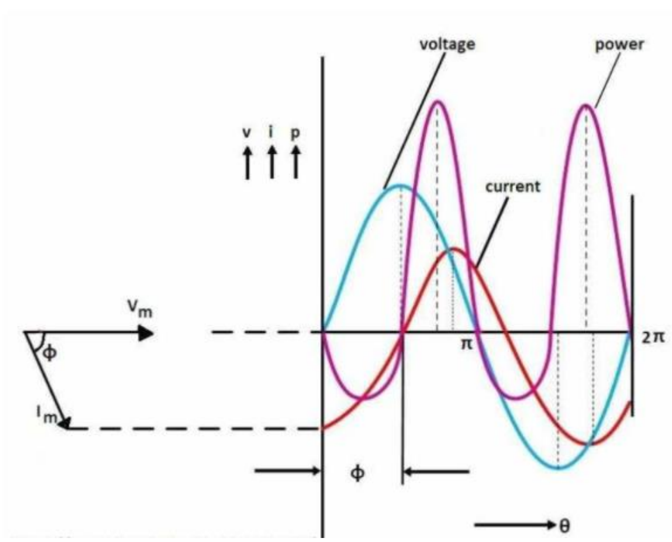
- RL series circuit
- RC series circuit
- RLC series circuit

RL SERIES CIRCUIT



In an RL series circuit, a pure resistance (R) is connected in series with a coil having the pure inductance (L). To draw the phasor diagram of RL series circuit, the current *I* (RMS value) is taken as reference vector because it is common to both elements.

Voltage drop V_R is in phase with current vector, whereas, the voltage drop in inductive reactance V_L leads the current vector by 90^o since current lags behind the voltage by 90^o in the purely inductive circuit. The vector sum of these two voltage drops is equal to the applied voltage V (RMS value).

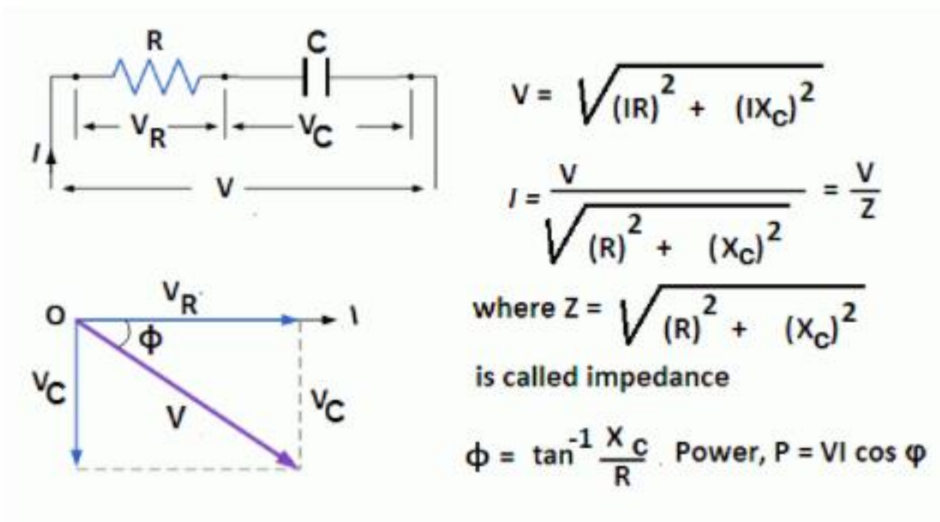


The power waveform for RL series circuit is shown in the figure. In this figure, voltage wave is considered as a reference. The points for the power waveform are obtained from the product of the corresponding instantaneous values of voltage and current.

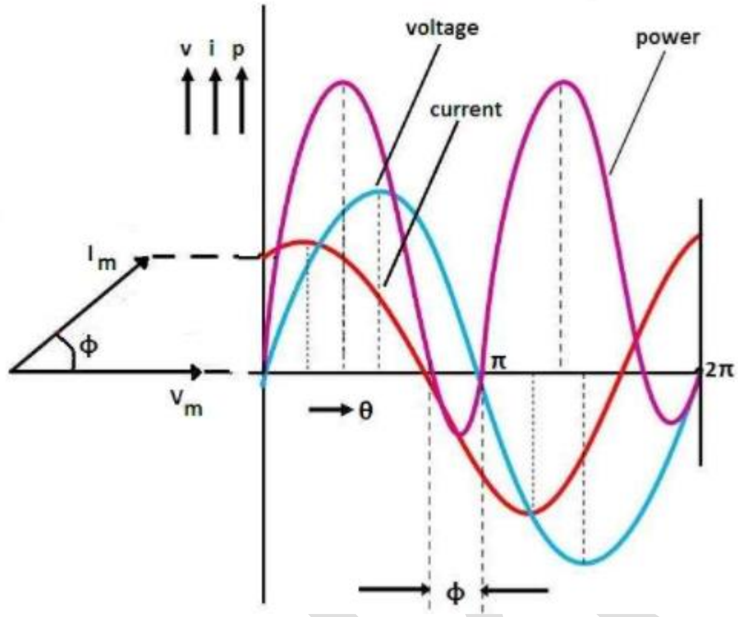
It is clear from the power waveform that power is negative between 0 and φ and between 180^o and ($180^o + φ$). The power is positive during rest of the cycle.

Since the area under the positive loops is greater than that under the negative loops, the net power over a complete cycle is positive. Hence a definite quantity of power is consumed by the RL series circuit. But power is consumed in resistance only; inductance does not consume any power.

RC SERIES CIRCUIT



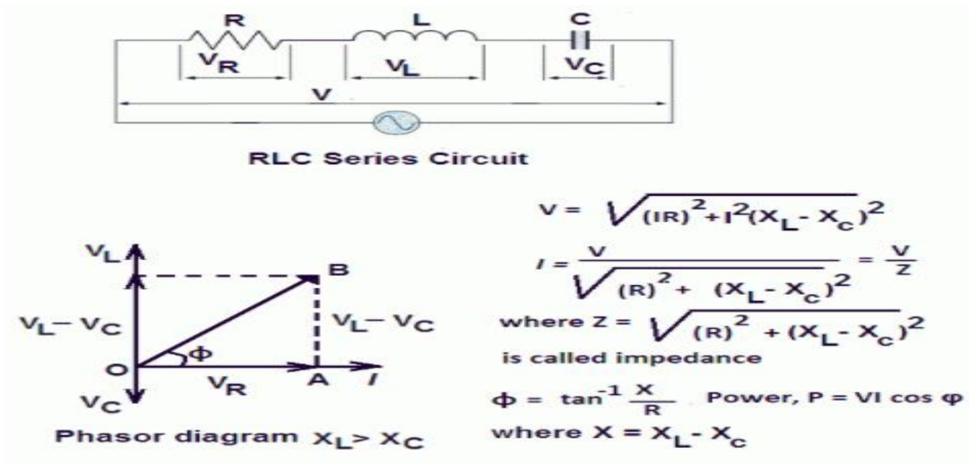
In an RC series circuit, a pure resistance (R) is connected in series with a pure capacitor (C). To draw the phasor diagram of RC series circuit, the current *I* (RMS value) is taken as reference vector. Voltage drop V_R is in phase with current vector, whereas, the voltage drop in capacitive reactance V_C lags behind the current vector by 90^o, since current leads the voltage by 90^o in the pure capacitive circuit. The vector sum of these two voltage drops is equal to the applied voltage V (RMS value).



The power waveform for RC series circuit is shown in the figure. In this figure, voltage wave is considered as a reference. The points for the power waveform are obtained from the product of the corresponding instantaneous values of voltage and current. It is clear from the power waveform that power is negative between (180^o – φ) and 180^o and between (360^o – φ) and 360^o. The power is positive during rest of the cycle.

Since the area under the positive loops is greater than that under the negative loops, the net power over a complete cycle is positive. Hence a definite quantity of power is consumed by the RC series circuit. But power is consumed in resistance only; capacitor does not consume any power.

RLC SERIES CIRCUIT



In an RLC series circuit a pure resistance (R), pure inductance (L) and a pure capacitor (C) are connected in series. To draw the phasor diagram of RLC series circuit, the current *I* (RMS value) is taken as the reference vector. The voltages across three components are represented in the phasor diagram by three phasors V_R, V_L and V_C respectively.

The voltage drop V_L is in phase opposition to V_C. It shows that the circuit can either be effectively inductive or capacitive. In the figure, phasor diagram is drawn for the inductive circuit. There can be three cases of RLC series circuit.

- When $X_L > X_C$, the phase angle φ is positive. In this case, RLC series circuit behaves as an RL series circuit. The circuit current lags behind the applied voltage and power factor is lagging. In this case,

  if the applied voltage is represented by the equation;
  $v = V_m \sin \omega t$ then, the circuit current will be represented by the equation;
  $i = I_m \sin(\omega t - \varphi)$.

- When $X_L < X_C$, the phase angle φ is negative. In this case, the RLC series circuit behaves as an RC series circuit. The circuit current leads the applied voltage and power factor is leading. In this case, the circuit current will be represented by the equation:

  $i = I_m \sin(\omega t + \varphi)$.

- When $X_L = X_C$, the phase angle φ is zero. In this case, the RLC series circuit behaves like a purely resistive circuit. The circuit current is in phase with the applied voltage and power factor is unity. In this case, the circuit current will be represented by the equation:

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

Example

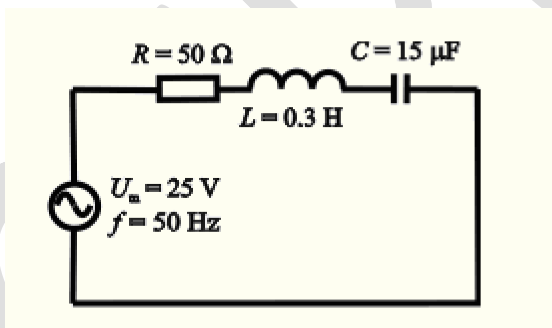
In AC circuit is composed of a serial connection of:

a resistor with resistance 50 Ω,

a coil with inductance 0.3 H

and a capacitor with capacitance 15 μF.

The circuit is connected to an AC voltage source with amplitude 25 V and frequency 50 Hz. Determine the amplitude of electric current in the circuit and a phase difference between the voltage and the current.



We write down the quantities given in the assignment:

Resistance of resistor	$R = 50\ \Omega$
Inductance of the coil	$L = 0.3$ H
Capacitance	$C = 15\ \mu F = 15 \cdot 10^{-6}$ F
Amplitude of AC voltage source	$U_m = 25$ V
Frequency of source	$f = 50$ Hz

Resistor, coil and capacitor are connected in series.

Quantities that we want to determine:

Amplitude of the current in the circuit	$I_m = ?$ (A)
Phase difference between the voltage and the current in the circuit	$\varphi = ?$ (°)

How to solve this task:

1. We evaluate the current amplitude. We apply Ohm's law for the alternating current, which expresses the relationship between an overall impedance Z, a voltage amplitude of the source U_m and a current amplitude I_m. For this calculation, we know all the quantities from assignment.

2. Electric current flowing through all the components connected in series is of the same size; however the voltage on the components is out of phase with the current. To obtain the phase difference (shift) between voltage and current we use a phasor diagram.

A phasor is an "arrow" that we use to plot the current and voltage values on individual components of the circuit into a phasor diagram. Its magnitude reflects the amplitude of the voltage or current, and its direction indicates the phase angle.

Drawing a phasor diagram for a series circuit:

We plot the values of voltage and current on individual components in the AC circuit into the phasor diagram.

The current is of the same size on all the components, the phasor of current Im is therefore the same for all the components and is usually drawn in the positive direction of the x-axis.

The phasor of voltage is on the resistor UR parallel to the current phasor, because the phase difference between the voltage and current is zero – in this case voltage and current are in phase. In the figure the phasor is illustrated by green.

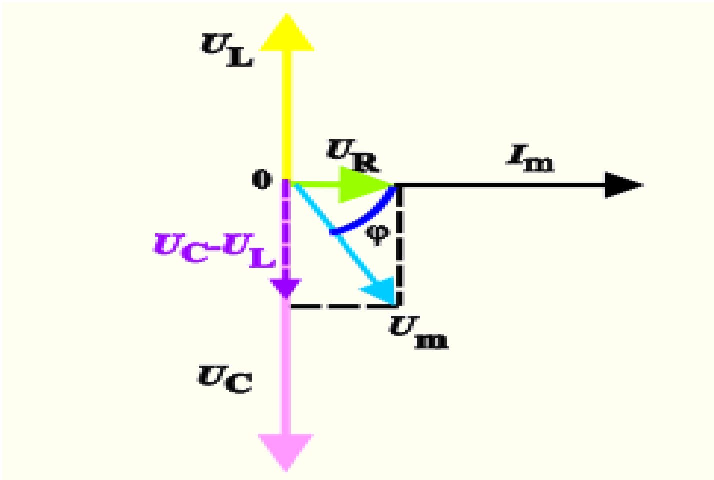
The voltage on the coil UL leads the current by π/2 (quarter of a period), therefore we draw its phasor pointing upwards – in the positive direction of the imaginary y-axis. We consider the fact that the phasors rotate in a counter clockwise direction. In the figure, this phasor is represented by yellow.

The current on the capacitor leads the voltage UC by π/2. Therefore we draw the phasor pointing downward – that is in negative direction of the y-axis. This phasor is represented by pink.

The amplitude of the overall voltage is obtained by a "vector sum" of phasors of the voltage on individual components. First, we subtract the voltage on the capacitor UC from the voltage on the coil UL (in the picture drawn in purple). Then we add this vector and the vector of the voltage on the resistor UR. The phasor of the voltage amplitude of the entire circuit is represented by light blue.

A phase difference between the voltage and the current is said to be the angle φ between the current phasor and the overall voltage phasor. The angle φ is drawn by navy blue

For an RLC circuit and the given quantities the phasor diagram looks like this:



Phasor diagram

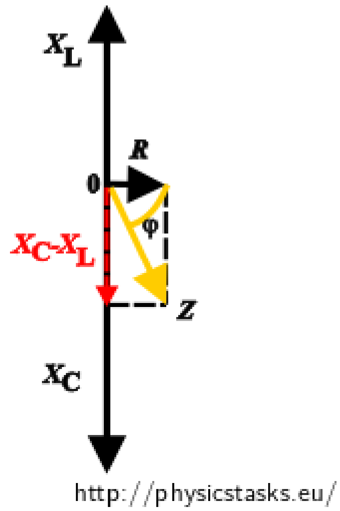
In the following figures the phasor diagrams are not illustrated by the same colour

To get the total impedance *Z* from the phasor diagram, instead of the voltage on individual components in the phasor diagram we plot the inductance X_L, the capacitance X_C and the resistance *R*.

From Ohm's law we know that:

$$U_C = I_m X_C, \quad U_L = I_m X_L, \quad U_R = I_m R.$$

Since the current through all the components is the same, the impedances of individual elements are proportional to the voltage, so we can draw a diagram similar to the voltage phasors.



To calculate the impedance Z we use the rectangular triangle we can see in the phasor diagram. The impedance Z is evaluated by using Pythagorean theorem.

$$Z^2 = R^2 + (X_C - X_L)^2$$

or:

$$Z^2 = R^2 + (X_L - X_C)^2.$$

The difference between the relationships is whether the current leads voltage or the voltage leads the current. The size of the impedance Z is however not affected

By substituting the relations of inductance and capacitance we obtain:

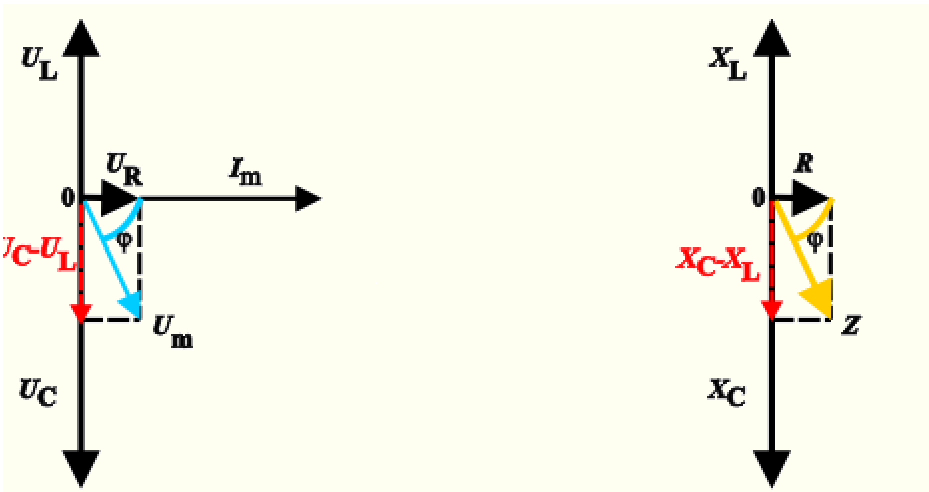
$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

The formula for expressing the impedances Z from Ohm's law is:

$$Z = \frac{U_m}{I_m} = \sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}$$

We determine the amplitude of the current I_m. We can easily derive

$$I_m = \frac{U_m}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}$$



The phase shift is expressed from the phasor diagram usually in the form:

$$\operatorname{tg}\varphi = \frac{U_L - U_C}{U_R} = \frac{I_m\omega L - \frac{I_m}{\omega C}}{I_m R} = \frac{\omega L - \frac{1}{\omega C}}{R} = \frac{X_L - X_C}{R}.$$

When we draw a phasor diagram and a phase difference, the formula

$$\operatorname{tg}\varphi = \frac{U_L - U_C}{U_R} = \frac{X_L - X_C}{R}$$

can be replaced by the formula

$$\operatorname{tg}\varphi = \frac{U_C - U_L}{U_R} = \frac{X_C - X_L}{R}.$$

We must be careful in interpreting the results. In the first case the numerator says that we consider the case when the voltage leads the current (similarly as on the coil). In the second case, on the other hand, the current leads the voltage. We choose a suitable relationship either from the phasor diagram, where we can see the phase difference between the voltage and current, or we choose one of the relations and interpret the result through the sign of the resulting value. If you choose, for example, the second formula for expressing the phase difference and the resulting value has a plus sign, then the current leads the voltage. However, if the resulting value of the phase difference is negative, then the voltage leads the current.

The current amplitude:

$$I_m = \frac{U_m}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} =$$

$$= \frac{25}{\sqrt{50^2 + \left(2\pi \cdot 50 \cdot 0.3 - \frac{1}{2\pi \cdot 50 \cdot 15 \cdot 10^{-6}}\right)^2}} \text{ A} \doteq 0.2 \text{ A}$$

We can evaluate the **phase difference** by the impedance:

$$\text{tg}\,\varphi = \frac{\omega L - \frac{1}{\omega C}}{R} = \frac{2\pi \cdot 50 \cdot 0.3 - \frac{1}{2\pi \cdot 50 \cdot 15 \cdot 10^{-6}}}{50} \doteq -2.4$$

Or it can be evaluated by using the voltage on individual components in the circuit:

The voltage on individual components of the circuit is:

$$U_R = I_m R \doteq 0.2 \cdot 50 \text{ V} = 10 \text{ V}$$

$$U_L = I_m \omega L \doteq 0.2 \cdot 2\pi \cdot 50 \cdot 0.3 \text{ V} \doteq 18.85 \text{ V}$$

$$U_C = \frac{I_m}{\omega C} \doteq \frac{0.2}{2\pi \cdot 50 \cdot 15 \cdot 10^{-6}} \text{ V} \doteq 42.44 \text{ V}$$

We determine the size of the phase difference between the voltage and the current in the circuit from the phase diagram:

$$\text{tg}\,\varphi = \frac{U_L - U_C}{U_R} \doteq \frac{18.85 - 42.44}{10} \doteq -2.4$$

Both methods gave us the same result:

In the series RLC circuit the amplitude of the current is approximately:

I_m = 0.2 A.

The phase difference between the voltage and the current is about:

φ = -67°.

ZThe sign of the phase difference means that the current leads the voltage by about 67° (since the current leads the voltage, this circuit acts as a capacitor).

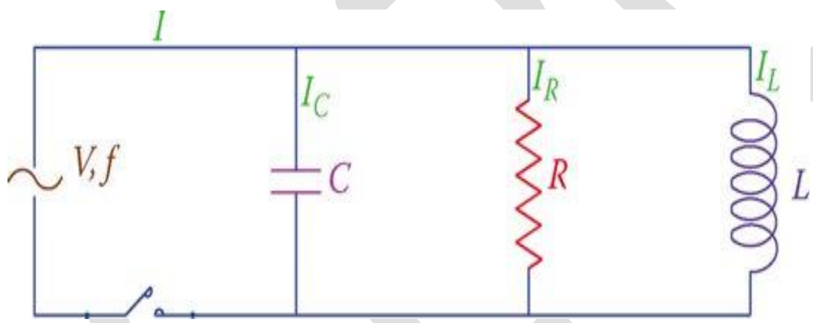
Parallel RLC Circuit

In parallel *RLC* circuits the three basic components are in parallel with each other, and, therefore, all are subject to the same voltage. The current for each branch, however, depends on the impedance of the branch and can be individually determined by employing **Ohm's law**.

For a parallel *RLC* circuit, the voltage is common for all the three types of components because it is the **same voltage** that is applied to each component. Nevertheless, the **currents in the three branches are not in phase with each other**. This means that the currents in the three branches do not simultaneously reach their peak values or zero values.

Hence, the total current cannot be determined by algebraically adding the individual values of the currents in the resistor, inductor, and capacitor.

A parallel *RLC* circuit is shown in **Figure 1**. As in the case of series *RLC* circuits, we need to find the total current and the power consumption for the whole circuit or for each individual branch.



For this circuit the voltage applied to each component in each branch is the same. Therefore, the current in each component can be found from dividing the voltage by the branch impedance. Then the currents can be added together.

However, because the currents in the three components are not in phase with each other (they do not reach their maximum and minimum values at the same time), they cannot be algebraically added together and must be added in vector form.

Figure 1 illustrates the vector representation of the three currents in a typical parallel *RLC* circuit. It shows that the current in the resistor is in phase with the applied voltage, the current in the capacitor leads the applied voltage (remember *ICE*) and the current in the inductor lags the voltage (remember *ELI*).

Furthermore, note that for this vector representation of the currents and voltage in a parallel *RLC* circuit, because the voltage is the common variable for all branches, you start by drawing the vector for the voltage as the reference vector. (In series *RLC* circuit you started this process by drawing the vector for the current.)

To find the total current in a parallel *RLC* circuit, one needs to find the vector sum of the currents in *R*, *L*, and *C*.

Because the current in the inductor and the current in the capacitor are 180° out of phase, in adding them together their values are subtracted from each other. Thus, the relationship for the total current of the circuit, *I*, and the individual component currents I_R, I_L, and I_C is

$$I = \sqrt{I_R^2 + (I_L - I_C)^2} \qquad (1)$$

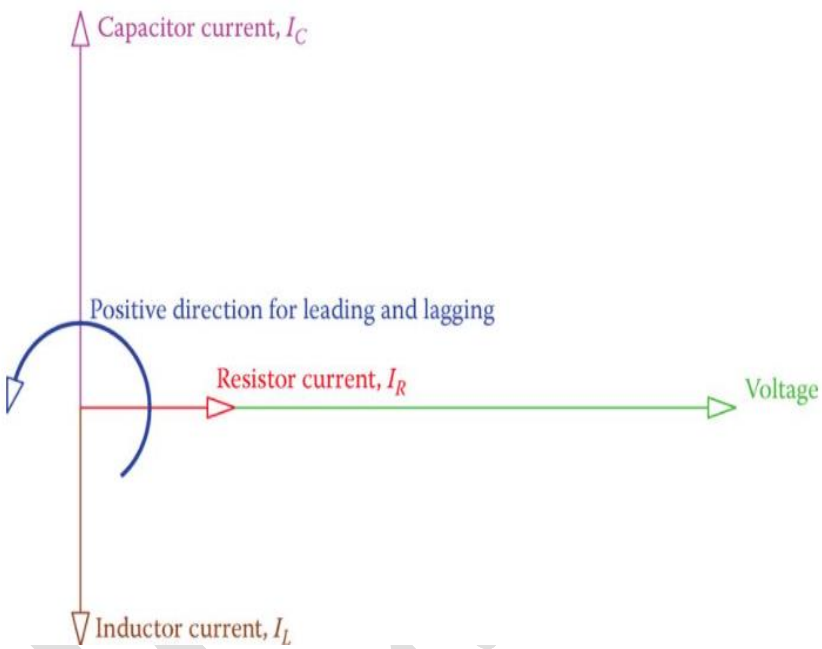


Figure 2 Vectors for the voltage and the three different currents in the *RLC* parallel circuit.

Parallel *RLC* Circuit Example 1

In the circuit shown in **Figure 3** the current is 1.8 A. If the current through the capacitor is 1.5 A, find the applied voltage and the resistance of the resistor.

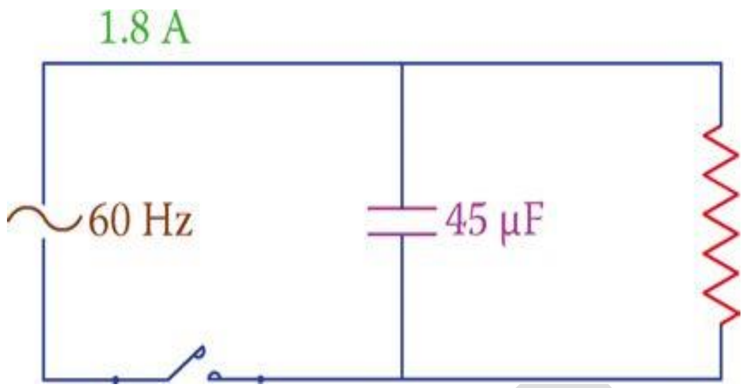


Figure 3 Circuit corresponding to **Example 1**.

Solution

For 60 Hz frequency, the reactance of the capacitor is

$$X_C = \frac{1}{2 * 3.14 * 60 * 0.000045} = 59\Omega$$

Thus, the applied voltage is

59∗1.5=88.5V59∗1.5=88.5V

Because this circuit has no inductor, the value of L in **Equation 1** is set to zero and the result is

$$I = \sqrt{I_R^2 + I_C^2}$$

Which leads to

$$I_R = \sqrt{1.8^2 - 1.5^2} = 0.995 = 1A$$

And the resistance of the resistor is

$$88.5 \div 1 = 88.5\Omega$$

If in **Equation 1**, the values for I_R, I_L, and I_C are replaced by $\frac{V}{R}$, $\frac{V}{X_L}$ and I is written as the ratio of the applied voltage to the circuit impedance Z, we have

$$\frac{V}{Z} = \sqrt{\left(\frac{V}{R}\right)^2 + \left(\frac{V}{X_L}\right)^2}$$

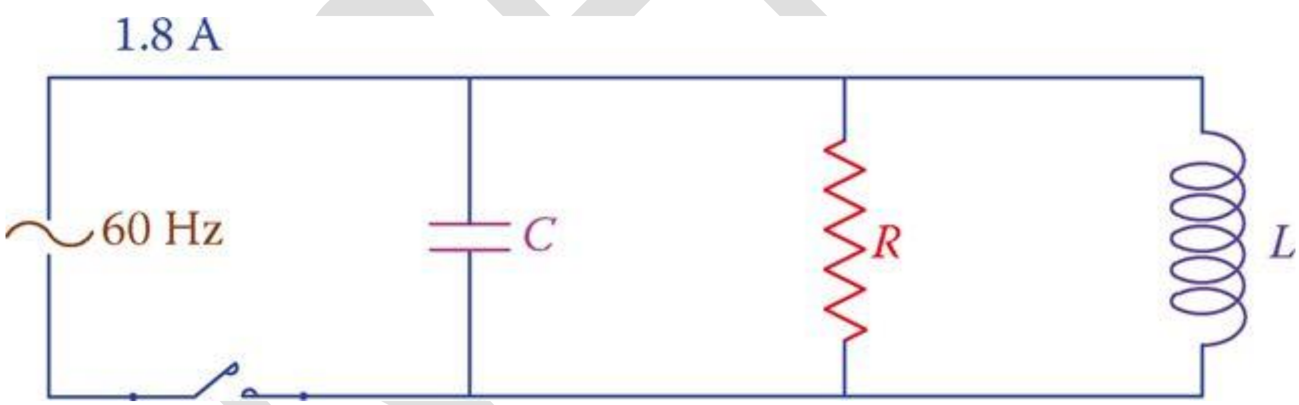
By omitting V from both sides the relationship between Z and R, L, and C can be found then as

$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2} \qquad (2)$$

Equation 2 can be used to find the equivalent impedance of the three components in parallel. The circuit current can also be found this way by dividing the applied voltage by Z or by directly multiplying 1/Z by the applied voltage.

Parallel *RLC* Circuit Example 2

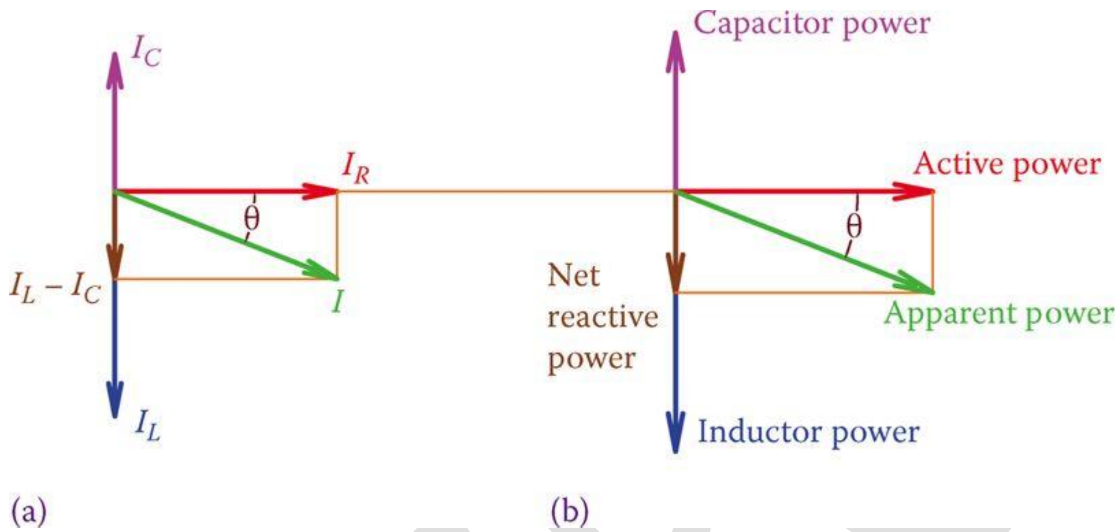
In the circuit shown in **Figure 4**, $R = 55\ \Omega$, $L = 0.08$ H, and $C = 1\ \mu$F, find the impedance of the circuit and the applied voltage.



$$X_L = 2 * 3.14 * 60 * 0.08 = 30.16\Omega$$
$$X_C = \frac{1}{2 * 3.14 * 60 * 0.000001} = 26.5\Omega$$
$$\frac{1}{Z} = \sqrt{\left(\frac{1}{55}\right)^2 + \left(\frac{1}{55} - \frac{1}{26.5}\right)^2} = \frac{1}{53.33}$$
$$Z = 53.33\Omega$$

Applied voltage = $V = ZI$ = (53.33) (1.8) = **96 V.**

Equation 2 also implies that the value for Z is smaller than R for parallel *RLC* circuits. A vector representation of I_R, I_L, I_C, and I is shown in **Figure 5**, which also shows the powers in the three components and the apparent power.



Reactive power is the vector sum of the inductive and capacitive powers. Depending on if inductive power (Q_L) or the capacitive power (Q_C) is larger the vectors for I and the apparent power S fall below or above the horizontal reference. The former implies that the current leads the voltage and the latter denotes that the current lags the voltage.

Because in practice the majority of applications (including home and industrial circuits) are parallel circuits, any circuit is categorized to be leading or lagging. If in a circuit the current leads the voltage, the circuit is said to be leading; if the current lags the voltage, the circuit is said to be lagging.

Power Factor in Parallel *RLC* Circuits

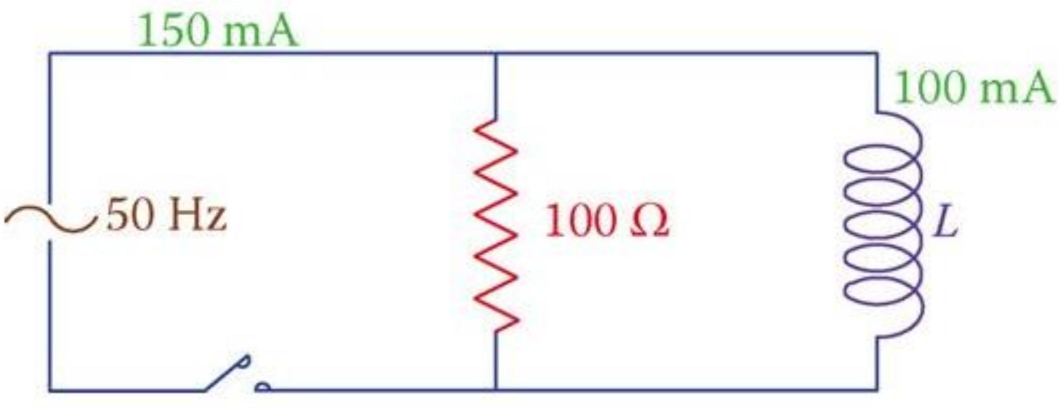
Figure 5 shows a lagging circuit. In practice, most of the circuits are lagging because of the presence of electric motors, unless the effects of electric motors are compensated by inserting capacitors that introduce capacitive power to a circuit (see power factor correction). The power factor in a parallel *RLC* circuit is determined from

$$pf = \frac{Z}{R} = \frac{I_R}{I} = \frac{Active\ Power}{Apparent\ Power} \qquad (3)$$

Note that the power factor by itself is not sufficient to describe a circuit. It has to be accompanied by the statement for leading or lagging. A circuit may have the same power factor in two cases, either leading or lagging. Sometimes the leading or lagging is attributed to the power factor. For example, one may say a circuit has a leading power factor of 0.90.

Parallel *RLC* Circuit Example 3

In the circuit shown in Figure 6, the total current is 150 mA and the current through the inductor is 100 mA. Determine what the applied voltage is. Also, knowing that the frequency is 50 Hz, find the value of *L*.



Solution

The applied voltage can be found by multiplying the resistor current by 100 Ω. Having only a resistor and an inductor in this circuit **Equation 1** leads to

$$I_R = \sqrt{I^2 - I_L^2} = \sqrt{150^2 - 100^2} = 0.1118A$$
$$V = 100 * 0.0008 = 11.18V$$
$$X_L = 11.18 \div 0.100 = 111.8\Omega$$
$$L = \frac{X_L}{2\pi f} = \frac{111.8}{2\pi * 50} = 35.6mH$$

In a parallel AC circuit, if the current leads the voltage, the circuit is said to be leading; if the current lags, the voltage the circuit is said to be lagging.

TYPES OF AC POWER

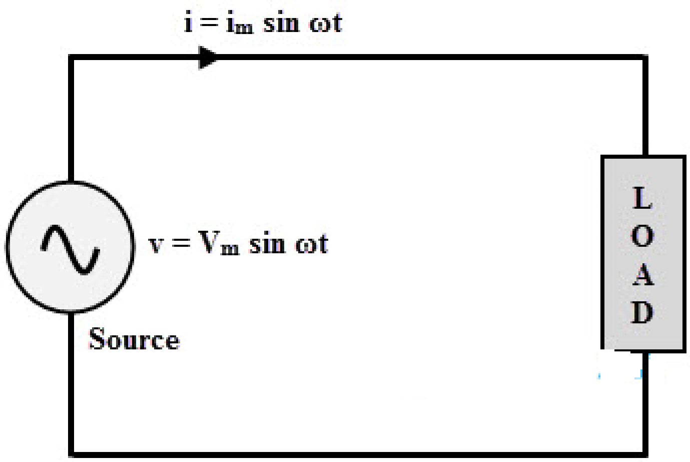
The power in any electrical circuit can be obtained by performing multiplication of voltage and current values in that circuit. This is applicable for both DC and AC circuits.

i.e., power = (Current value) x (Voltage value)

P = V x I

Power is measured in watts. In DC circuits and pure AC circuits without any non linear components, the current and voltage waveforms are ‘in phase’.

So the power at any instant of time in that circuit is obtained by multiplying the voltage and current. However, in case of AC circuits, this will not be so (as mentioned above the existence of phase shift).



Consider the above circuit in which AC supply is given to a load.Voltages and currents in the circuit are given as

$v = V_m \sin \omega t \Rightarrow v = \sqrt{2}\, V \sin \omega t$

$i = I_m \sin \omega t \Rightarrow i = \sqrt{2}\, I \sin (\omega t \pm \phi)$

Where V (= $V_m/\sqrt{2}$) and I (= $I_m/\sqrt{2}$) are the RMS values of applied voltage and current flowing through the circuit respectively. Φ is the phase difference between voltage and current, to which + sign indicates the leading phase angle while negative indicates the lagging phase angle.

Then the instantaneous power delivered to load by source is given by,

$p = vi = 2\, VI \sin wt \sin (\omega t \pm \phi)$

$= VI (\cos \phi – \cos (2\omega t \pm \phi)$

$p = VI \cos \phi\, (1 – \cos 2wt) \pm VI \sin \phi \sin 2wt$

The above power equation consists of two terms, namely

1. A term proportional to VI cos ϕ which is pulsating around the average value of VI cos ϕ
2. A term proportional to VI sin ϕ pulsating at twice the supply frequency, producing an average of zero over a cycle.

So there are 3 forms of powers in AC circuits. They are

1. Active power or True power or Real power
2. Reactive power
3. Apparent power

Active Power

The actual amount of power being dissipated or performs the useful work in the circuit is called as active or true or real power. It is measured in watts, practically measured in KW (kilowatts) and MW (megawatts) in power systems.

It is denoted by the letter P (capital) and it is equal to the average value of p = VI cos ϕ. It is the desired outcome of an electrical system which drives the circuit or load.

$P = VI \cos \phi$

Reactive Power

The average value of the second term in the above derived expression is zero, so the power contributed by this term is zero. The component, which is proportional to VI sin ϕ is called as reactive power, represented by the letter Q.

Even though it is a power, but not measured in watts as it is a non active power and hence, it is measured in Volt-Amperes- Reactive (VAR). The value of this reactive power can be negative or positive depends on the load power factor.

This is because inductive load consumes the reactive power while capacitive load generates the reactive power.

$Q = VI \sin \phi$

Significance of Reactive Power

The reactive power is one of the total power components that travel back and forth in the circuit or line. It can be termed as the rate of change of energy with respect to time that keeps on flowing from source to reactive components during positive half cycle and back to the components from source during negative cycle. Therefore, it never gets consumed by the load.

In the normal sense, this fictitious power is not at all a power but only a power-like measure of reactive component of the current. If there exist excess amount of reactive power, power factor is greatly reduced. This low power factor is undesirable in terms of operating efficiency and operational costs.

And also this power causes to draw additional current from the supply leads to additional losses and greater capacity of the equipments. That's why this power has been referred as the cholesterol of power lines in a joking manner.

In order to minimize losses and to increase the capacity of the available equipment, utility companies make use VAR compensation techniques or power factor correction equipments. Generally, these reactive compensation techniques are implemented at the load side.

However, this reactive power is useful for generating necessary magnetic fields for operation of inductive devices like transformers, AC motors, etc. It also helps to regulate the voltage in heavy power supply mechanisms.

Apparent Power

The complex combination of true or active power and reactive power is called apparent power. Without reference to any phase angle, the product of voltage and current gives the apparent power. The apparent power is useful for rating the power equipment.

It can also be expressed as the square of the current multiplied by the circuit's impedance. It is denoted by the letter S and measured in Volt-Amperes (VA), practical units include KVA (Kilo volt-amperes) and MVA (mega volt-amperes).

Apparent power = RMS voltage × RMS current

Apparent power, $S = V \times I$

In complex form, $S = V I^*$

$S = V \angle 0^0 \; I \angle \phi$ (for lagging load current)

$S = V I \angle \phi$

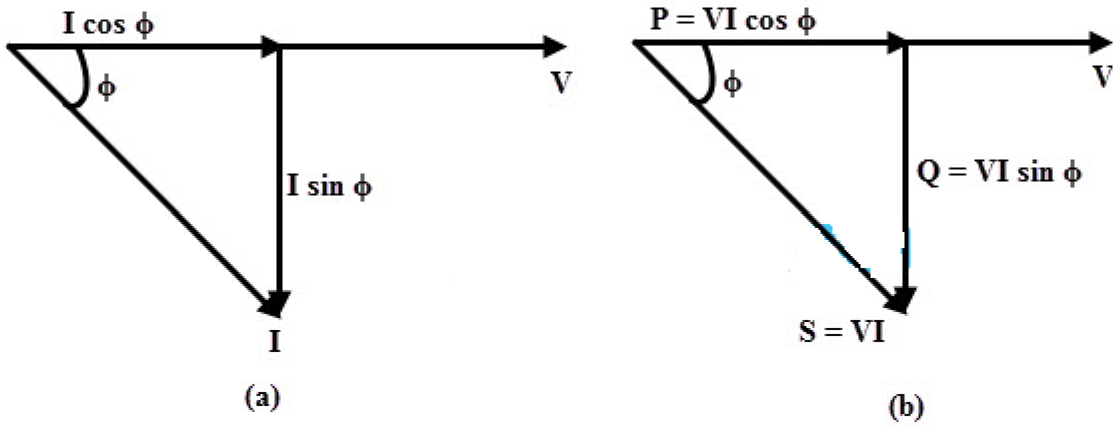
$S = V I \cos \phi + jV I \sin \phi$

$S = P + jQ$

Or $S = I^2 Z$

Power Triangle

The relation between active, reactive and apparent power can be expressed by representing quantities as vectors, which is also called as power triangle method as shown below. In this phasor diagram voltage is considered as reference vector. The voltage & current phasor diagram is the basis for the formation of the power triangle.



In figure (a), current lags the applied voltage by angle ϕ. The horizontal component of the current is I cos ϕ and the vertical component of the current is I sin ϕ. If each of the current phasor is multiplied by the voltage V, the power triangle is obtained as shown in the figure (b).

The active power is contributed by the component I cos ϕ in phase with voltage while reactive power is produced by the quadrature component.

Therefore, the apparent power or the hypotenuse of the triangle is obtained by combining real and reactive power vectorially.

Using Pythagoras's theorem, the sum of squares of the two adjacent sides (active power and reactive power) is equal to the square of the diagonal (apparent power). i.e.,

$(\text{Apparent power})^2 = (\text{Real Power})^2$

$S^2 = P^2 + Q^2$

$S = \sqrt{(Q^2 + P^2)}$

Where

S = apparent power measured in kilovolt amps, kVA

Q = reactive power measured in kilovolt amps reactive, kVAR

P = active power measured in kilowatts, kW

In terms of resistive, inductive and impedance elements, the power forms can be expressed as

Active power = P = I^2R

Reactive power = Q = I^2X

Apparent power = S = I^2Z

Where

X is inductance

Z is impedance.

Power Factor

The power factor is the cosine angle between the voltage and current. The power factor can be expressed in terms of the above discussed power forms. Consider the power triangle in above figure in which power factor is the ratio of active power to apparent power. Power factor defines the efficiency of the circuit.

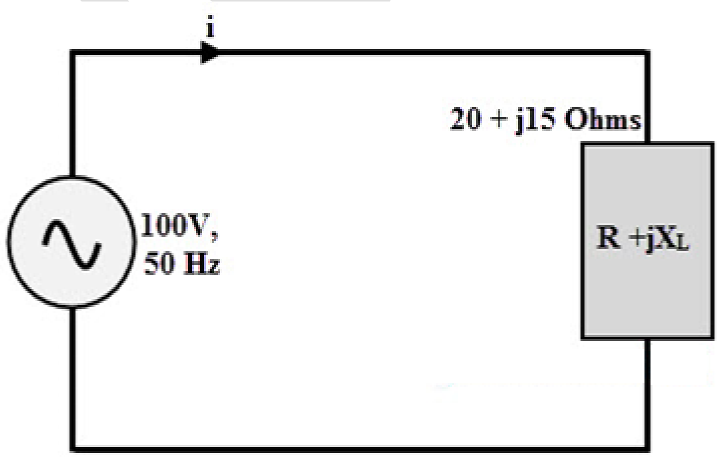
Power factor (PF) = (Active power in watts)/(Apparent power in volt amps)

PF = VI cos ϕ / VI

PF = cos ϕ

Example Problem

If an AC power supply of 100V, 50Hz is connected across a load of impedance, 20 + j15 Ohms. Then calculate the current flowing through the circuit, active power, apparent power, reactive power and power factor.



Given that, Z = R + jXL = 20 + j 15 Ω

Converting the impedance to polar form, we get

$Z = 25 \angle 36.87\ \Omega$

Current flowing through the circuit,

$I = V/Z = 100\angle 0^0\ /25 \angle 36.87$

$I = 4 \angle -36.87$

Active power, $P = I^2R = 42 \times 20 = 320$ watts

Or $P = VI \cos \phi = 100 \times 4 \times \cos (36.87) = 320.04 \approx 320$ W

Apparent power, $S = VI = 100 \times 4 = 400$ VA

Reactive power, $Q = \sqrt{(S^2 - P^2)}$

$= \sqrt{(400^2 - 320^2)} = 240$ VAr

Power factor, PF = $\cos \phi = \cos 36.87 = 0.80$ lagging.

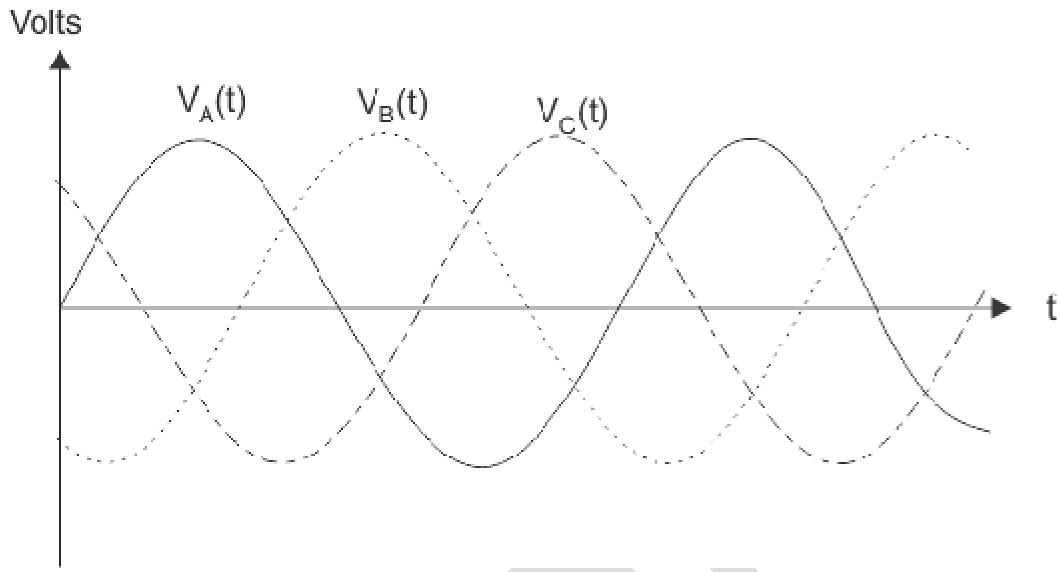
THREE PHASE CIRCUITS

There are two types of system available in electric circuit, single phase and **three phase system**. In single phase circuit, there will be only one phase, i.e the current will flow through only one wire and there will be one return path called neutral line to complete the circuit. So in single phase minimum amount of power can be transported. Here the generating station and load station will also be single phase. This is an old system using from previous time.

In 1882, new invention has been done on polyphase system, that more than one phase can be used for generating, transmitting and for load system. **Three phase circuit** is the polyphase system where three phases are send together from the generator to the load.

Each phase are having a phase difference of 120^o, i.e 120^o angle electrically. So from the total of 360^o, three phases are equally divided into 120^o each. The power in **three phase system** is continuous as all the three phases are involved in generating the total power. The sinusoidal waves for 3 phase system is shown below-

The three phases can be used as single phase each. So if the load is single phase, then one phase can be taken from the **three phase circuit** and the neutral can be used as ground to complete the circuit.



Why Three Phase is Preferred Over Single Phase?

There are various reasons for this question because there are numbers of advantages over single phase circuit. The three phase system can be used as three single phase line so it can act as three single phase system. The three phase generation and single phase generation is same in the generator except the arrangement of coil in the generator to get 120^o phase difference. The conductor needed in three phase circuit is 75% that of conductor needed in single phase circuit. And also the instantaneous power in single phase system falls down to zero as in single phase we can see from the sinusoidal curve but in three phase system the net power from all the phases gives a continuous power to the load.

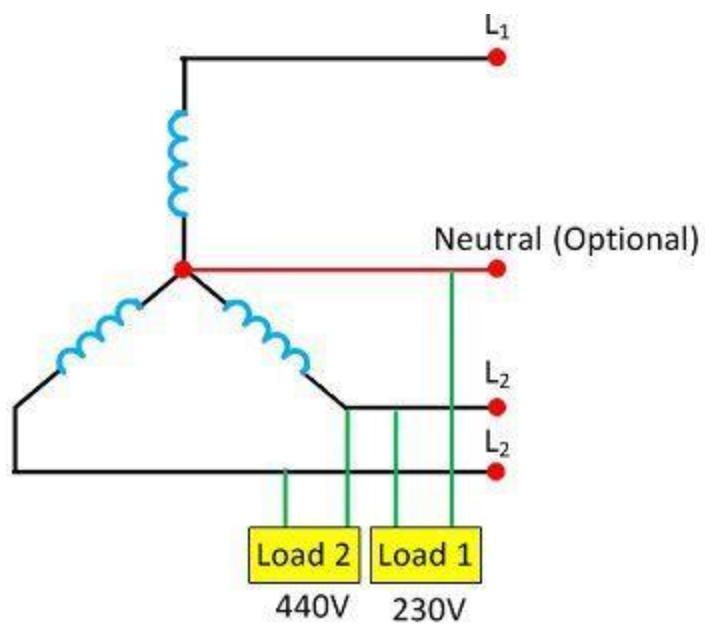
Till now we can say that there are three voltage source connected together to form a three phase circuit and actually it is inside the generator. The generator is having three voltage sources which are acting together in 120^o phase difference. If we can arrange three single phase circuit with 120^o phase difference, then it will become a three phase circuit. So 120^o phase difference is must otherwise the circuit will not work, the three phase load will not be able to get active and it may also cause damage to the system.

The size or metal quantity of three phase devices is not having much difference. Now if we consider the transformer, it will be almost same size for both single phase and three phase because transformer will make only the linkage of flux. So the three phase system will have higher efficiency compared to single phase because for the same or little difference in mass of transformer, three phase line will be out whereas in single phase it will be only one. And losses will be minimum in three phase circuit. So overall in conclusion the three phase system will have better and higher efficiency compared to the single phase system.
In three phase circuit, connections can be given in two types:

1. Star connection
2. Delta connection

Star Connection

The star connection requires four wires in which there are three phase conductors and one neutral conductor. Such type of connection is mainly used for long distance transmission because it has a neutral point. The neutral point passes the unbalanced current to the earth and hence make the system balance.



3 - phase Star Connected System

The star connected three phase systems gives two different voltages, i.e., the 230 V and 440V. The voltage between the single phase and the neutral is 230V, and the voltage between the two phases is equal to the 440V.

Voltage and Current Values in Three-Phase star Systems

When we measure voltage and current in three-phase systems, we need to be specific as to *where* we're measuring.

Line voltage refers to the amount of voltage measured between any two line conductors in a balanced three-phase system. With the above circuit, the line voltage is roughly 208 volts.

Phase voltage refers to the voltage measured across any one component (source winding or load impedance) in a balanced three-phase source or load.

For the circuit shown above, the phase voltage is 120 volts. The terms *line current* and *phase current* follows the same logic: the former referring to the current through any one line conductor, and the latter to the current through any one component.

Y-connected sources and loads always have line voltages greater than phase voltages, and line currents equal to phase currents. If the Y-connected source or load is balanced, the line voltage will be equal to the phase voltage times the square root of 3:

For “Y” circuits:

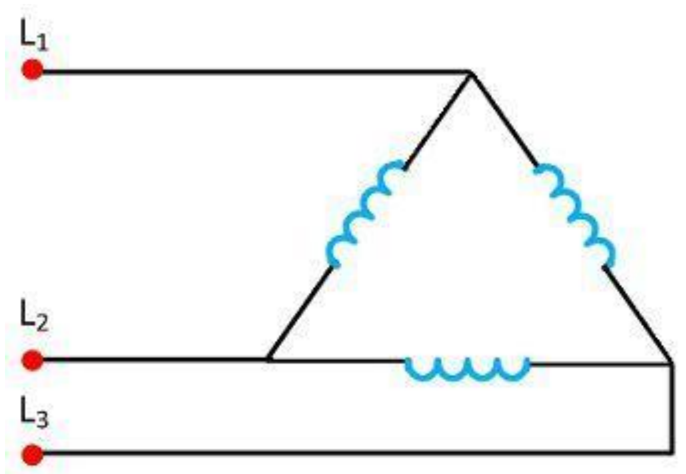
$$E_{line} = \sqrt{3}\ E_{phase}$$

$$I_{line} = I_{phase}$$

However, the “Y” configuration is not the only valid one for connecting three-phase voltage source or load elements together.

Delta Connection

The delta connection has three wires, and there is a no neutral point. The delta connection is shown in the figure below. The line voltage of the delta connection is equal to the phase voltage.



3 - Phase Delta Connection Circuit Globe

Kirchhoff's Voltage Law in Delta Connections

One quick check of this is to use Kirchhoff's Voltage Law to see if the three voltages around the loop add up to zero. If they do, then there will be no voltage available to push current around and around that loop, and consequently, there will be no circulating current.

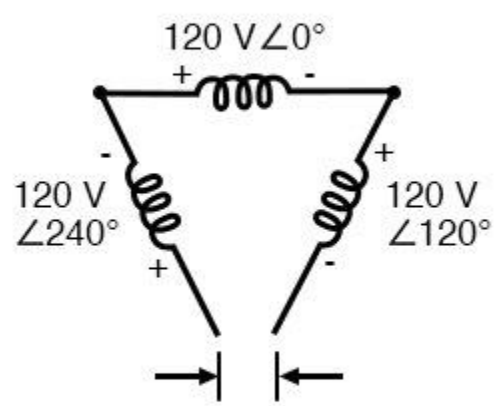
Starting with the top winding and progressing counter-clockwise, our KVL expression looks something like this:

$$(120\ V\angle 0°) + (120\ V\angle 240°) + (120\ V\angle 120°)$$

Does it all equal 0 ?

Yes!

Indeed, if we add these three vector quantities together, they do add up to zero. Another way to verify the fact that these three voltage sources can be connected together in a loop without resulting in circulating currents is to open up the loop at one junction point and calculate the voltage across the break: (figure below)



E_{break} should equal 0 V

The voltage across open Δ should be zero.

Starting with the right winding (120 V ∠ 120°) and progressing counter-clockwise, our KVL equation looks like this:

$$(120\ V\angle 120°) + (120\ V\angle 0°) + (120\ V\angle 240°) + E_{break} = 0$$

$$0 + E_{break} = 0$$

$$E_{break} = 0$$

Sure enough, there will be zero voltage across the break, telling us that no current will circulate within the triangular loop of windings when that connection is made complete.

Having established that a Δ-connected three-phase voltage source will not burn itself to a crisp due to circulating currents, we turn to its practical use as a source of power in three-phase circuits.

Because each pair of line conductors is connected directly across a single winding in a Δ circuit, the line voltage will be equal to the phase voltage.

Conversely, because each line conductor attaches at a node between two windings, the line current will be the vector sum of the two joining phase currents.

Not surprisingly, the resulting equations for a Δ configuration are as follows**:**

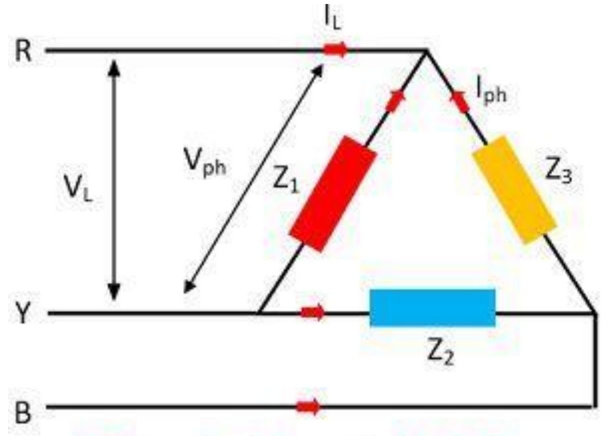
For Δ ("delta") circuits:

$$E_{line} = E_{phase}$$

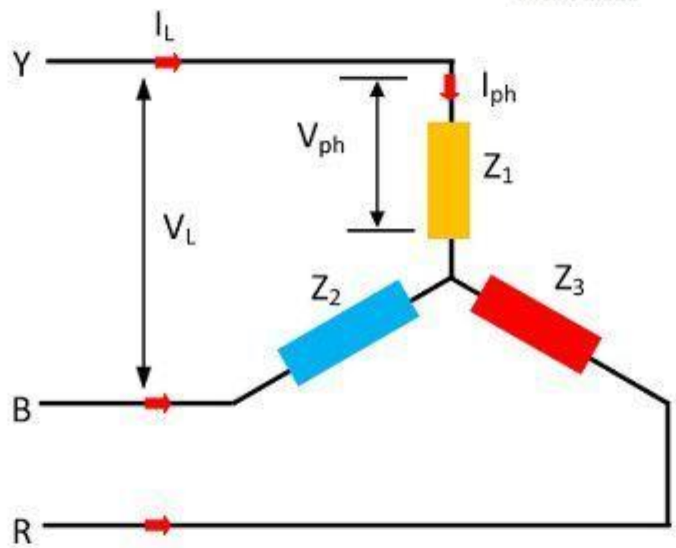
$$I_{line} = \sqrt{3}\ I_{phase}$$

Connection of Loads in Three Phase System

The loads in the three-phase system may also connect in the star or delta. The three phase loads connected in the delta and star is shown in the figure below.



3 - Phase Load Connected in Delta

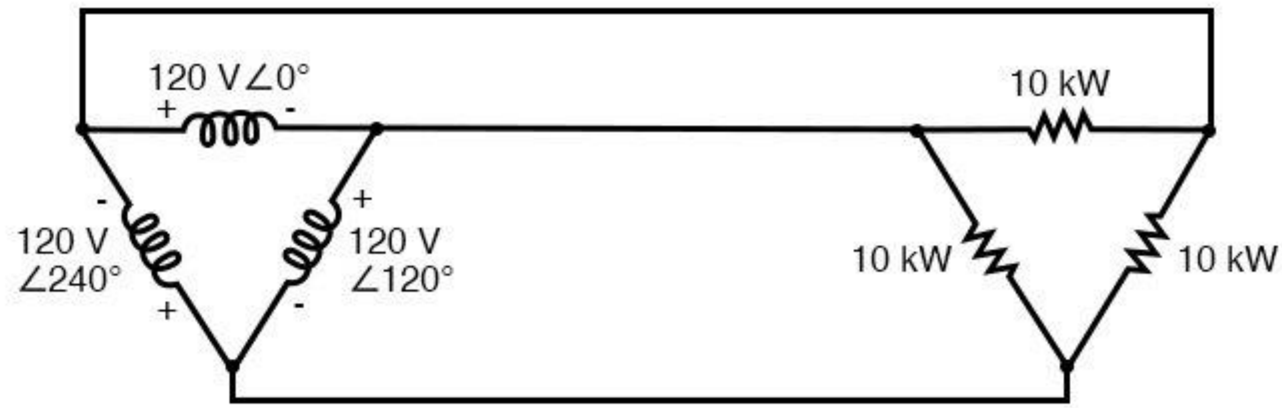


3 - Phase Load Connected in Star

The three phase load may be balanced or unbalanced. If the three loads (impedances) Z_1, Z_2 and Z_3 has the same magnitude and phase angle then the three phase load is said to be a balanced load. Under balance condition, all the phases and the line voltages are equal in magnitude.

Delta Connection Example Circuit Analysis

Let's see how this works in an example circuit: (Figure below)



The load on the Δ source is wired in a Δ.

The load on the Δ source is wired in a Δ.

With each load resistance receiving 120 volts from its respective phase winding at the source, the current in each phase of this circuit will be 83.33 amps:

$$I = \frac{P}{E}$$

$$I = \frac{10\text{ kW}}{120\text{ V}}$$

$$I = 83.33\text{ A} \quad \text{(for each load resistor and source winding)}$$

$$I_{line} = \sqrt{3}\, I_{phase}$$

$$I_{line} = \sqrt{3}\,(83.33\text{ A})$$

$$I_{line} = 144.34\text{ A}$$

Advantages of the Delta Three-Phase System

So each line current in this three-phase power system is equal to 144.34 amps, which is substantially more than the line currents in the Y-connected system we looked at earlier.

One might wonder if we've lost all the advantages of three-phase power here, given the fact that we have such greater conductor currents, necessitating thicker, more costly wire.

The answer is no. Although this circuit would require three number 1 gauge copper conductors (at 1000 feet of distance between source and load this equates to a little over 750 pounds of copper for the whole system), it is still less than the 1000+ pounds of copper required for a single-phase system delivering the same power (30 kW) at the same voltage (120 volts conductor-to-conductor).

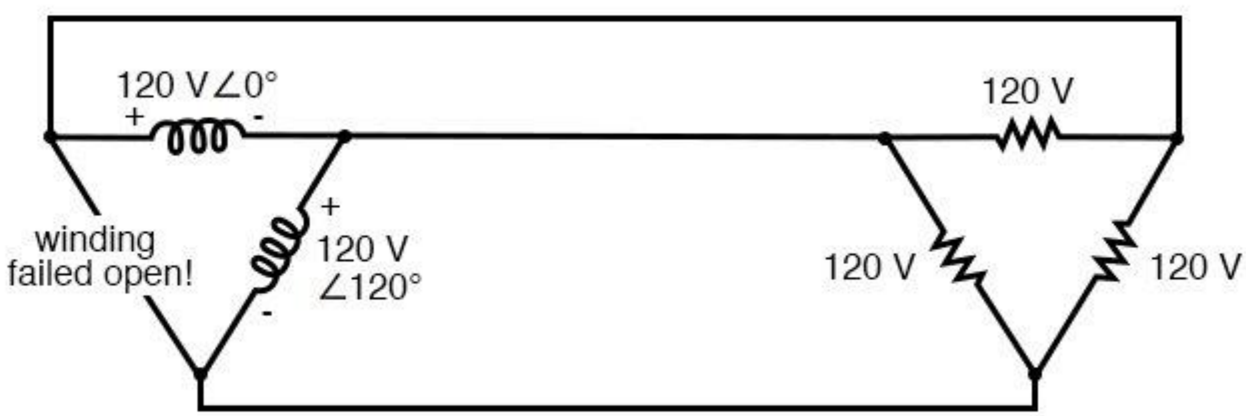
One distinct advantage of a Δ-connected system is its lack of a neutral wire. With a Y-connected system, a neutral wire was needed in case one of the phase loads were to fail open (or be turned off), in order to keep the phase voltages at the load from changing.

This is not necessary (or even possible!) in a Δ-connected circuit.

With each load phase element directly connected across a respective source phase winding, the phase voltage will be constant regardless of open failures in the load elements.

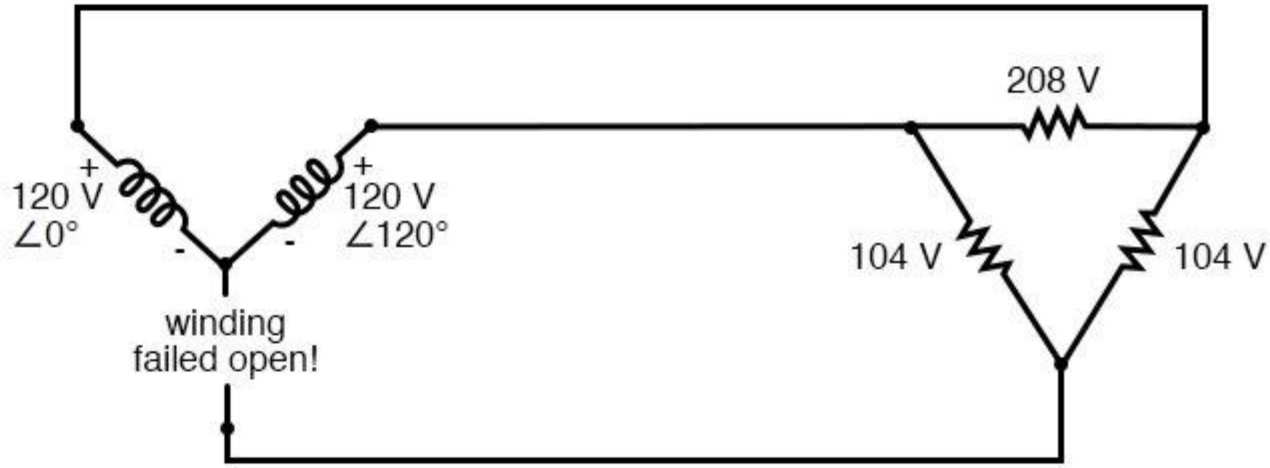
Perhaps the greatest advantage of the Δ-connected source is its fault tolerance.

It is possible for one of the windings in a Δ-connected three-phase source to fail open (Figure below) without affecting load voltage or current!



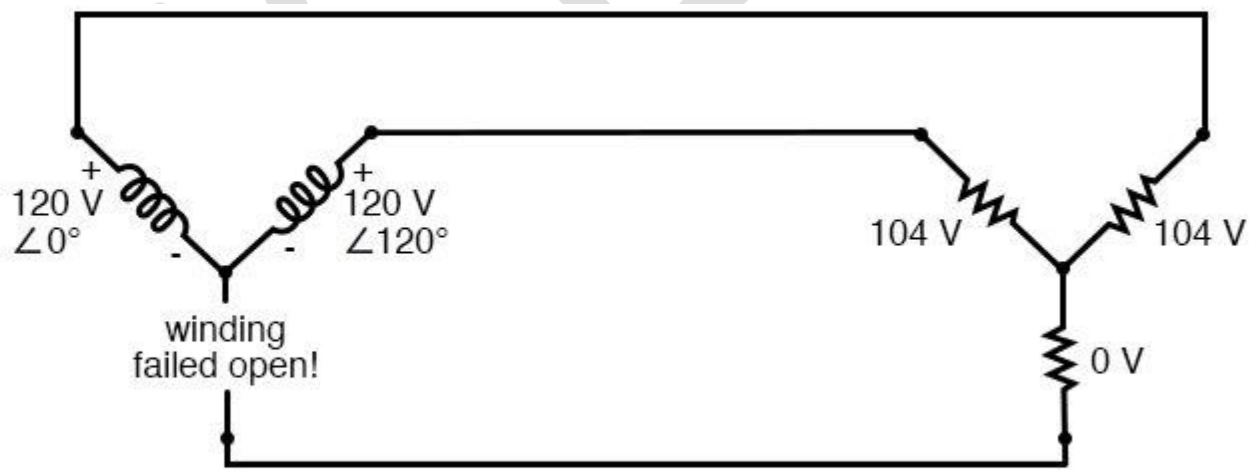
Even with a source winding failure, the line voltage is still 120 V, and the load phase voltage is still 120 V. The only difference is extra current in the remaining functional source windings.

The only consequence of a source winding failing open for a Δ-connected source is increased phase current in the remaining windings. Compare this fault tolerance with a Y-connected system suffering an open source winding in the figure below.



Open "Y" source winding halves the voltage on two loads of a Δ connected the load.

With a Δ-connected load, two of the resistances suffer reduced voltage while one remains at the original line voltage, 208. A Y-connected load suffers an even worse fate (Figure below) with the same winding failure in a Y-connected source.



Open source winding of a "Y-Y" system halves the voltage on two loads and loses one load entirely.

In this case, two load resistances suffer reduced voltage while the third loses supply voltage completely! For this reason, Δ-connected sources are preferred for reliability.

However, if dual voltages are needed (e.g. 120/208) or preferred for lower line currents, Y-connected systems are the configuration of choice.

REVIEW:

- The conductors connected to the three points of a three-phase source or load are called *lines*.
- The three components comprising a three-phase source or load are called *phases*.
- *Line voltage* is the voltage measured between any two lines in a three-phase circuit.
- *Phase voltage* is the voltage measured across a single component in a three-phase source or load.
- *Line current* is the current through any one line between a three-phase source and load.
- *Phase current* is the current through any one component comprising a three-phase source or load.
- In balanced "Y" circuits, the line voltage is equal to phase voltage times the square root of 3, while the line current is equal to phase current.

For "Y" circuits:

$$E_{line} = \sqrt{3}\ E_{phase}$$

$$I_{line} = I_{phase}$$

- In balanced Δ circuits, the line voltage is equal to phase voltage, while the line current is equal to phase current times the square root of 3.

For Δ ("delta") circuits:

$$E_{line} = E_{phase}$$

$$I_{line} = \sqrt{3}\ I_{phase}$$

- Δ-connected three-phase voltage sources give greater reliability in the event of winding failure than Y-connected sources. However, Y-connected sources can deliver the same amount of power with less line current than Δ-connected sources.

THREE PHASE POWER MEASUREMENT USING WATTMETER

Various methods are used for **measurement of three phase power** in three phase circuits on the basis of number of wattmeters used. We have three methods to discuss:

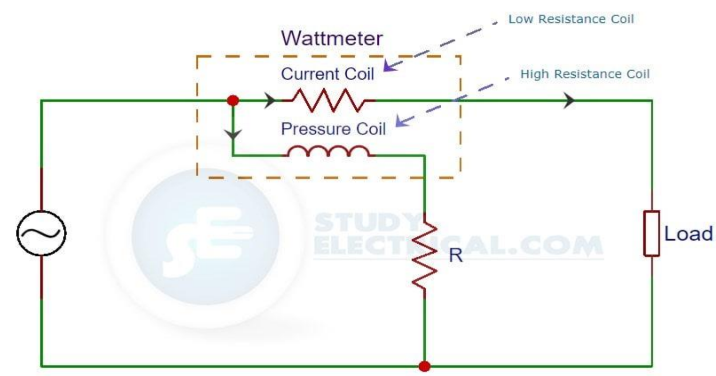
1. Three wattmeters method
2. Two wattmeters method
3. Single wattmeter method.

What is a Wattmeter?

A wattmeter is an equipment used to measure power in a circuit. It consists of two types of coils. They are:

- A **Current Coil** that possesses a *low resistance*.
- A **Pressure or Potential Coil** that possesses a *high resistance*.

The current coil is connected in series with the line carrying current. The pressure coil is connected across the two points whose potential difference is to be measured. Refer the figure for the connections of a wattmeter.



Connection of a Wattmeter

A wattmeter shows a reading which proportional to the product of three values. They are

- Current (I) through its current coil.
- Potential difference (V) across its pressure coil.
- Cosine of the angle between voltage and current (Cosϕ).

$$P = VICos(\phi)$$

A comparison between the methods of measuring power in a three-phase circuit is shown in the table below.

Three Wattmeter Method	Used for measurement of 3 phase, 4 wire circuits. Both balanced and unbalanced loads.
One Wattmeter Method	Used in Balanced 3 phase, 3 wire load circuit.
Two Wattmeter Method	Used in both balanced and unbalanced 3 phase, 3 wire circuits

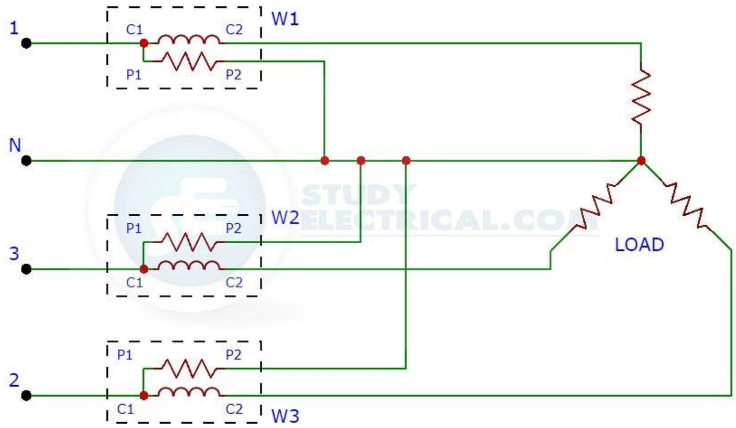
Let us discuss one by one each method in detail.

Three Wattmeter Method

Now we will explain the measurement three-phase power measurement using three wattmeter method.

Three wattmeter method is used to measure power in 3 phase, 4-wire circuits. However, this method can also be used in 3 phase, 3 wire delta connected load, where power consumed by each load is required to be determined separately.

The figure below shows the three wattmeter connection of 3 phase, 4 wire star connected load.



Three Wattmeter Method

As indicated in the figure, the three wattmeters are connected in each of the three phases to measure three-phase power usage of the load whether star or delta connected.

The current coil of each wattmeter carries the current of one phase only and the pressure coil measures the phase voltage of the phase. Hence, each wattmeter measures the power in a single phase. The total power in the load is given by the algebraic sum of the readings of the three wattmeters.

$$P = W1 + W2 + W3$$

where , W1 = V1*I1 , W2 = V2*I2, W3 = V3*I3

Disadvantages of Three Wattmeter Method

While using three wattmeter method following difficulty is met with:

- In the case of 3 phase, 3 wire star connected load, it is difficult to get a neutral point which is required for connection. In special cases, when this method is necessary to use, an 'artificial star' can be formed.
- In case of delta connected circuits, the difficulty in using this method is due to fact that the phase coils are required to be broken for inserting current coils of wattmeters.

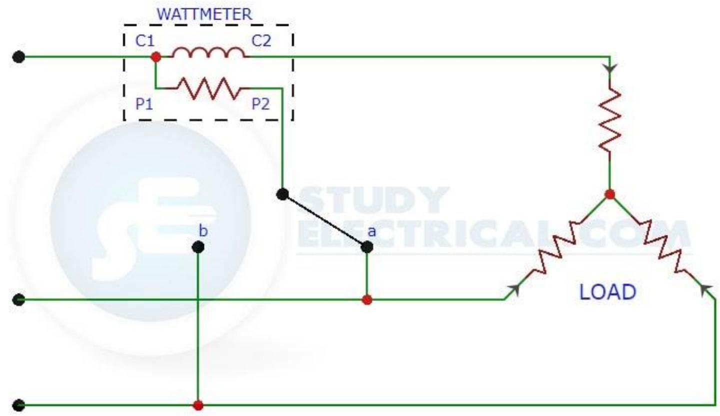
To measure power it is not necessary to use three wattmeter, even two wattmeters can be used for the purpose.

Except for 3 phase, 4 wire unbalanced load, three-phase power are measured using only Two Wattmeter Method.

One Wattmeter Method

The next method we are going to discuss is the one wattmeter method.

In this method of three-phase power measurment, the current coil is connected in any one line and the pressure coil is connected alternatively between this and the other two lines. The connection diagram is shown in the figure below.



One Wattmeter Method

So we will get two readings for a balanced load. The two readings so obtained, correspond to those obtained by the normal two wattmeter method.

A balanced load is a load that draws the same current from each phase of the three-phase system, while an unbalanced load has at least one of those currents different from the rest.

In balanced 3-wire, 3-phase load circuit the power in each phase is equal. Therefore, the total power of the circuit can be determined by multiplying the power measured in any one phase by three.

Total power in balanced load = 3 x Power per Phase

= 3 x Wattmeter reading

Disadvantages of One Wattmeter Method

This method is not of as much universal application as the two wattmeter method because it is restricted to fairly balance loads only. Even a slight degree of unbalance in the loading produce a large error in the measurement.

However, it may be conveniently applied, for instance, when it is desired to find the power input to a factory motor in order to check the load up on the motor.

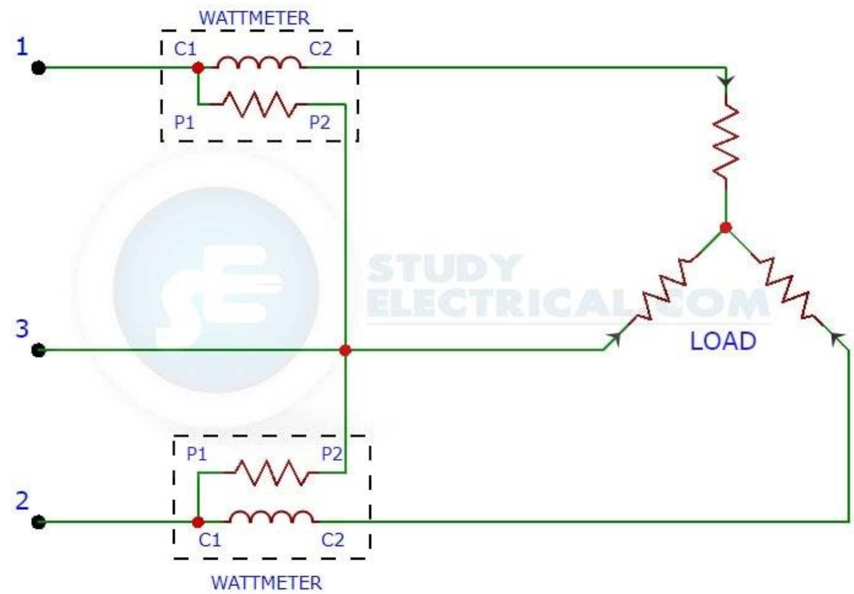
Two Wattmeter Method

As the name indicates, in this method two wattmeters are used to measure three-phase power. This is the most popular method among the three.

This method is generally used for the measurement of power in 3 phase, 3-wire load circuits. It can be used to measure power in star/delta connected load in balanced or unbalanced condition.

Remember a balanced load is a load that draws the same current from each phase of the three-phase system, while an unbalanced load has at least one of those currents different from the rest.

In two wattmeter method, the current coils of the two wattmeters are inserted in any two lines and pressure coil of each wattmeter is joined to the third line. Refer the figure below for better understanding.



Two Wattmeter Method

The figure above shows the two wattmeter connection of star connected load. Similarly, delta connected loads are also used. Two wattmeter method can be used irrespective of balanced or unbalanced load.

The algebraic sum of two wattmeter reading gives the total power in the 3-phase, 3 wire star-connected or delta connected load circuits whether the load is balanced or unbalanced.

$$P = W1 + W2$$

THREE PHASE BALANCED SYSTEMS PROBLEMS

1. The input power to a 3-phase a.c. motor is measured as 5kW. If the voltage and current to the motor are 400V and 8.6A respectively, determine the power factor of the system?

Power P=5000W,

line voltage V_L = 400 V,

line current, I_L = 8.6A and

power, $P = \sqrt{3}\, V_L I_L \cos\varphi$

Hence

power factor = $\cos\varphi = \frac{P}{\sqrt{3}\, V_L I_L}$

$= \frac{5000}{\sqrt{3}\,(400)\,(8.6)}$

= **0.839**

2. Two wattmeters are connected to measure the input power to a balanced 3-phase load by the two-wattmeter method. If the instrument readings are 8kW and 4kW, determine (a) the total power input and (b) the load power factor.

(a)Total input power,

$P = P_1 + P_2$ =8+4=**12kW**

(b) $\tan\varphi = \sqrt{3}(P_1 - P_2)/(P_1 + P_2)$

$=\sqrt{3}\ (8 - 4) / (8 + 4)$

$=\sqrt{3}\ (4/12)$

$=\sqrt{3}(1/3)$

$= 1/\sqrt{3}$

Hence $\varphi = \tan^{-1}\frac{1}{\sqrt{3}} = 30^\circ$

Power factor= $\cos\varphi = \cos 30^\circ$ =**0.866**

3. Two wattmeters connected to a 3-phase motor indicate the total power input to be 12kW. The power factor is 0.6. Determine the readings of each wattmeter.

If the two wattmeters indicate $P1$ and $P2$ respectively

Then $P1 + P2 = 12\text{kW}$ ---(1)

$\tan\varphi = \sqrt{3}(P1 - P2)/(P1 + P2)$

And power factor=0.6= $\cos\varphi$.

Angle $\varphi = \cos^{-1}0.6 = 53.13^\circ$ and

$\tan 53.13^\circ = 1.3333$.

Hence

$1.3333 = \sqrt{3}(P1 - P2)/12$

From which,

$P1 - P2 = 12(1.3333)/\sqrt{3}$

i.e. $P1 - P2 = 9.237\text{kW}$ ----(2)

Adding Equations (1) and (2) gives:

$2P1 = 21.237$

i.e $P1 = 21.237/2$

= 10.62kW Hence wattmeter 1 reads 10.62kW From Equation (1), wattmeter 2 reads

$(12-10.62) = 1.38\text{kW}$

4. Three loads, each of resistance 30, are connected in star to a 415 V, 3-phase supply. Determine

(a) the system phase voltage, (b) the phase current and (c) the line current.

A '415 V, 3-phase supply' means that 415 V is the line voltage, V_L

(a) For a star connection, $V_L = \sqrt{3}V_p$ Hence phase voltage, $V_p = V_L/\sqrt{3}$

$= 415/\sqrt{3}$

= **239.6 V or 240 V**

correct to 3 significant figures

(b) Phase current, $I_p = V_p/R_p$

= 240/30

= **8 A**

(c) For a star connection, Ip = IL Hence the line current, IL = **8 A**

5. Three identical coils, each of resistance 10*ohm* and inductance 42mH are connected (a) in star and (b) in delta to a 415V, 50 Hz, 3-phase supply. Determine the total power dissipated in each case.

(a) **Star connection**

Inductive reactance,

$X_L = 2\pi f L = 2\pi (50)(42\times10^{-3}) = 13.19$

Phase impedance,

$Z_p = \sqrt{(R^2 + X_L^2)}$

$= \sqrt{(10^2 + 13.19^2)} = 16.55$

Line voltage, $V_L = 415\ V$

And phase voltage,

$V_P = V_L/\sqrt{3} = 415/\sqrt{3} = 240\ V.$

Phase current,

$I_p = V_p/Z_p = 240/16.55 = 14.50\ A.$ Line current,

$I_L = I_p = 14.50\ A.$

Power factor= $\cos\varphi = R_p/Z_p = 10/16.55 = 0.6042$ lagging.

Power dissipated,

$\boldsymbol{P} = \sqrt{3}\ V_L I_L \cos\varphi = \sqrt{3}\ (415)(14.50)(0.6042)$ = **6.3kW** (Alternatively,

$\boldsymbol{P} = 3I^2R = 3(14.50)^2(10) =$ **6.3kW**)

(b) **Delta connection**

$V_L = V_p = 415$ V,

$Z_p = 16.55$_, $\cos\varphi = 0.6042$ lagging (from above). Phase current,

$I_p = V_p/Z_p$ =415/16.55=25.08A. Line current,

$I_L = \sqrt{3} I_p = \sqrt{3}(25.08)$=43.44A.

Power dissipated,

$\boldsymbol{P} = \sqrt{3}\ V_L I_L \cos\varphi$

$= \sqrt{3}\ (415)(43.44)(0.6042)$ = **18.87kW**

(Alternatively,

$\boldsymbol{P} = 3I^2R$

$= 3(25.08)^2(10)$ =**18.87 kW)**

6. A 415V, 3-phase a.c. motor has a power output of 12.75kW and operates at a power factor of 0.77 lagging and with an efficiency of 85 per cent. If the motor is delta-connected, determine (a) the power input, (b) the line current and (c) the phase current.

(a) Efficiency=power output/power input.

Hence

(85/100)=12.750 power input from which, **Power input** = 12. 750 × 10085

= **15 000W** or **15Kw**

(b) Power, $P = \sqrt{3}\ V_L I_L \cos\varphi$, hence

(c) **line current**,

$I_L = P/\ \sqrt{3}\ (415)\ (0.77)$

= 15 000/ √3 (415) (0.77)

= **27.10A**

(d) For a delta connection, $I_L = \sqrt{3}\ I_p$,

Hence

Phase current, $I_p = I_L/\sqrt{3}$

= 27.10 /√3

= 15.65A

7. A 400V, 3-phase star connected alternator supplies a delta-connected load, each phase of which has a resistance of 30_ and inductive reactance 40_. Calculate (a) the current supplied by the alternator and (b) the output power and the kVA of the alternator, neglecting losses in the line between the alternator and load.

A circuit diagram of the alternator and load is shown in Fig.

(a) Considering the load:

Phase current, $I_p = V_p/Z_p$

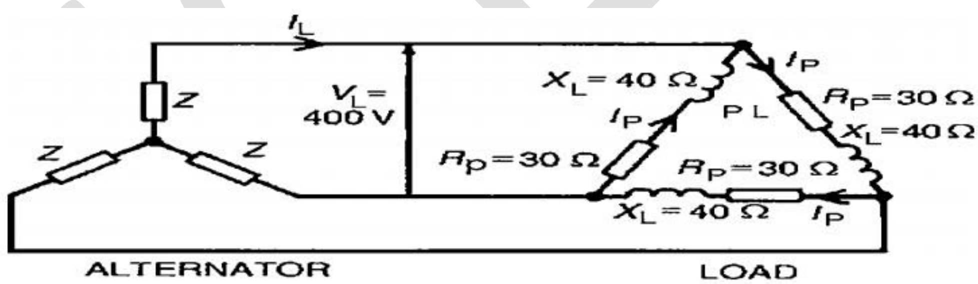
$V_p = V_L$ for a delta connection,

Hence V_p =400V.

Phase impedance,

$Z_p = \sqrt{(R2+X_L2)}$

$= \sqrt{(302 + 402)} = 50$



Figure

Hence $I_p = V_p/Z_p = 400/50 = 8A$.

For a delta-connection,

Line current, $I_L = \sqrt{3}\, I_p = \sqrt{3}\,(8) = 13.86\ A$.

Hence **13.86A is the current supplied by the alternator**.

(b) Alternator output power is equal to the power Dissipated by the load

I.e. $P = \sqrt{3}\, V_L I_L \cos\varphi$, Where $\cos\varphi = R_p/Z_p = 30/50 = 0.6$.

Hence $P = \sqrt{3}\,(400)\,(13.86)\,(0.6) =$ **5.76kW**.

Alternator output kVA,

$S = \sqrt{3}\, V_L I_L = \sqrt{3}\,(400)\,(13.86)$

9.60 kVA.

MODULE IV

GENERATION OF POWER

INTRODUCTION

We divide the power system into three parts; **power generation**, transmission, and distribution. In this article, we will discuss **power generation**. Actually, in power generation, one form of energy gets converted into electrical energy. We produce electrical energy from various natural sources.

We classify these sources into two types renewable sources and non-renewable sources. In a present power system, most of the electrical energy gets generated from non-renewable sources like coal, oil, and natural gases.

But these sources are limitedly available. So, we have to use these sources carefully and always find an alternate source or move on to renewable sources.

The renewable sources include solar, wind, water, tidal, and biomass. These sources are the environment-friendly, free and infinite resources available. Let us get more information about renewable sources.

Solar Energy System

It is the best alternative source for power generation. There are two ways, to generate electrical energy from sunlight.

1. We can create electricity directly by using photovoltaic (PV) cell. The photovoltaic cell is made up of silicon. Many cells are connected in series or parallel to make a solar panel.
2. We can produce heat (solar thermal) with the help of mirrors in the sunlight, and we use this heat to convert water into steam. This high-temperature steam rotates the turbines.

Advantages of Solar Energy System

1. The transmission cost is zero for a stand-alone solar system.
2. Solar electricity generation system is environment-friendly.
3. The maintenance cost is low.
4. It is an ideal source for remote locations that cannot link to the grid.

Disadvantages of Solar Energy System

1. Initial expenses are high.

2. Require large area for bulk production.
3. Solar electricity generation system is weather-dependent.
4. Solar energy storage (battery) is costly.

Wind Energy System

Wind turbines are used to convert wind energy into electrical energy. Wind flows due to temperature changes in the atmosphere. Wind turbines turn wind energy into kinetic energy. The rotating kinetic energy rotates the induction generator, and that generator converts kinetic energy into electrical energy.

Advantages of Wind Energy System

1. Wind energy is an unlimited, free and clean source of energy.
2. The operating cost is almost zero.
3. A wind electricity generating system can generate power in a remote location.

Disadvantage of Wind Energy System

1. It cannot produce the same amount of electricity at all time.
2. It needs a big open area.
3. It makes noise.
4. The construction process of a wind turbine is expensive.
5. It gives lower electricity output.
6. It poses threats from flying birds.

Hydro Energy System

The power obtained from river or ocean water is called hydropower. Hydro power plants are work based on the gravitational effects. Here we store water in a dam or reservoir. When we allow falling the water, the movement of this water as it flows downstream towards the penstock causes kinetic energy that rotates the turbines.

Advantages of Hydro Energy System

1. It can be used in the service instantly.
2. After this process, water can be used for irrigation and other purposes.

3. Dams are designed for an extended period and so it can contribute to the generation of electrical energy for many years.
4. Running and maintenance costs are low.
5. No fuel transportation is required.

Disadvantages of Hydro Energy System

1. The initial cost of a hydel power plant is high.
2. Hydropower plants are located in the hilly area, and it is very far from the load. So, they require a long transmission line.
3. The construction of dams can flood towns and cities.
4. It is also weather-dependent.

Coal Energy System

A thermal power plant produces electricity by burning coal in the boiler. Heat is used to convert water into steam. This high pressure and high-temperature steam flowing into the turbine spins a generator to produce electrical energy.

After it passes through the turbine, the steam gets cooled in a condenser and reuse in the boiler to generate steam again. Thermal power plant works according to Rankine cycle.

Advantages of Coal Energy System

1. Coal is cheap.
2. It has less initial cost compared to renewable power plants.
3. It requires less space than a hydel plant.
4. We can construct a thermal power plant at any place because coal can be transport to the plant irrespective of its location.
5. Construction and commissioning of thermal power plants take lesser time than a hydel plant.

Disadvantages of Coal Energy System

1. Coal is a non-renewable energy source.
2. The operating cost is high and variable according to the price of fuel.

3. It pollutes the atmosphere due to smoke and fumes.
4. It requires a huge quantity of water.

Nuclear Energy System

The working of nuclear power is almost the same as a thermal power plant. In a thermal power plant, coal is used in the boiler to produce heat.

In a nuclear power plant, uranium is used in the nuclear reactor to generate heat. In both power plants, heat energy gets converted into electrical energy.

1kg of uranium can produce energy same as the energy produced by burning of 4500 tonnes of coal or 2000 tonnes of oil.

Advantages of Nuclear Energy System

1. It requires less space than a thermal power plant and a hydropower plant.
2. It can produce an unusually high amount of electrical energy from a single plant.
3. It does not emit CO_2
4. A nuclear power plant needs a small quantity of fuel.

Disadvantages of Nuclear Energy System

1. It has a high initial construction cost.
2. It has high operating and maintenance costs.
3. It has radioactive waste.
4. It has a high risk of radio-activity and explosion.

Installed Electric Capacity in India

Yearly gross electricity generation by source (GWh) (2016-2017)

Source	Generation (GWh)
Coal	944,861
Oil	275

Gas	49,094
Diesel	
Nuclear	37,916
Hydro	122,313
Mini-hydro	7,673
Solar	12,086
Wind	46,011
Biomass	14,159

INTRODUCTION TO HYDRO ELECTRIC POWER STATION

Hydroelectric power plant

Working principle

Hydroelectric power plant (Hydel plant) utilizes the potential energy of water stored in a dam built across the river. The potential energy of the stored water is converted into kinetic energy by first passing it through the penstock pipe. The kinetic energy of the water is then converted into mechanical energy in a water turbine. The turbine is coupled to the electric generator. The mechanical energy available at the shaft of the turbine is converted into electrical energy by means of the generator.

Because gravity provides the force which makes the waterfall, the energy stored in the water is called gravitational potential energy.

Layout of Hydroelectric power plant

Fig. shows the schematic representation of a Hydroelectric power plant.

The main components are

- **Water reservoir**
- **Dam**
- **Spillway**
- **Gate**
- **Pressure tunnel**
- **Surge tank**
- **Penstock**
- **Water turbine**
- **Draft tube**
- **Tail race level**
- **Powerhouse**

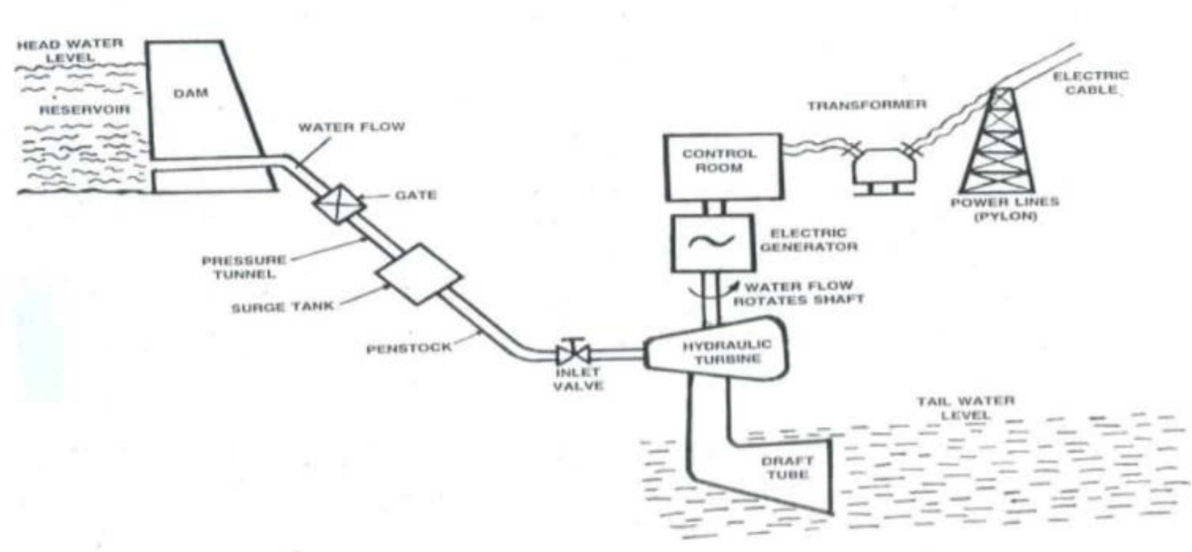


Fig.Layout of Hydro electric Power plant

Water reservoir:

In a reservoir the water collected from the catchment area during the rainy season is stored behind a dam. Catchment area gets its water from rains and streams. Continuous availability of water is a basic necessity for a hydroelectric power plant. The level of the water surface in the reservoir is called the Headwater level. The water head available for power generation depends on the reservoir height.

Dam:

The purpose of the dam is to store the water and to regulate the out going flow of water. The dam helps to store all the incoming water. It also helps to increase the head of the water. In order to generate a required quantity of power, it is necessary that a sufficient head is available.

Spillway:

Excess accumulation of water endangers the stability of dam construction. Also in order to avoid the overflow of water out of the dam especially during rainy seasons spillways are provided. This prevents the rise of the water level in the dam. Spillways are passages that allow the excess water to flow to a different storage area away from the dam.

Gate:

A gate is used to regulate or control the flow of water from the dam.

Pressure tunnel:

It is a passage that carries water from the reservoir to the surge tank.

Surge tank:

A surge tank is a small reservoir or tank in which the water level rises or falls due to sudden changes in pressure. There may a sudden increase of pressure in the penstock pipe due to sudden backflow of water, as the load on the turbine is reduced. This sudden rise of pressure in the penstock pipe is known as water hammer.

Penstock:

Penstock pipe is used to bring water from the dam to the hydraulic turbine. Penstock pipes are made up of steel or reinforced concrete. The turbine is installed at a lower level from the dam. Penstock is provided with a gate valve at the inlet to completely close the water supply.

It has a control valve to control the water flow rate into the turbine. Water turbine or hydraulic turbine (Prime mover): The hydraulic turbine converts the energy of water into mechanical energy. The mechanical energy (rotation) available on the turbine shaft is coupled to the shaft of an electric generator and electricity is produced. The water after performing the work on the turbine blade is discharged through the draft tube.

The prime movers which are in common use are Pelton wheel, Kaplan turbine, Francis turbine.

Draft tube:

Draft tube is connected to the outlet of the turbine. It converts the kinetic energy available in the water into pressure energy in the diverging portion. Thus, it maintains a pressure of just above the atmospheric at the end of the draft tube to move the water into a tailrace. Water from the tailrace is released for irrigation purposes.

Tailrace level:

Tailrace is a water path to lead the water discharged from the turbine to the river or canal. The water held in the tailrace is called the Tailrace water level.

Power House:

The powerhouse accommodates the water turbine, generator, transformer, and control room. As the water rushes through the turbine, it spins the turbine shaft, which is coupled to the electric generator. The generator has a rotating electromagnet called a rotor and a stationary part called a stator. The rotor creates a magnetic field that produces an electric charge in the stator. The charge is transmitted as electricity. The step-up transformer increases the voltage of the current coming from the stator. The electricity is distributed through power lines.

Classification of Hydroelectric power plant

Hydroelectric power plants are usually classified according to the available of head of water

• High head power plants

• Medium head power plants

• Low head power plants

High head power plants: When the operating head of water exceeds 70 meters, the plant is known as High head power plant. Pelton wheel turbine is the prime mover used.

Medium head power plants: When the water ranges from 15 to 70 meters, then the power plant is known as a Medium head power plant. It uses Francis Turbine.

Low head power plants: When the head is less than 15 meters, the plant is named as Low head power plant. It uses Francis or Kaplan turbine as the prime mover.

Advantages of hydroelectric power plant

1. The water source is perennially available. No fuel is required to be burnt to generate electricity. It is aptly termed as 'the white coal'. Water passes through turbines to produce work and downstream its utility remains undiminished for irrigation of farms and quenching the thirst of people in the vicinity.

2. The running costs of hydropower installations are very low as compared to thermal or nuclear power stations. In thermal stations, besides the cost of fuel, one has to take into account the transportation cost of the fuel also.

3. There is no problem with regard to the disposal of ash as in a thermal station. The problem of

emission of polluting gases and particulates to the atmosphere also does not exist. Hydropower does not produce any greenhouse effect, cause the pernicious acid rain and emit obnoxious NO.

4. The hydraulic turbine can be switched on and off in a very short time. In a thermal or nuclear power plant the steam turbine is put on turning gear for about two days during start-up and shut-down.

5. The hydraulic power plant is relatively simple in concept and self-contained in operation. Its system reliability is much greater than that of other power plants.

6. Modern hydropower equipment has a greater life expectancy and can easily last 50 years or more. This can be compared with an effective life of about 30 years of a thermal or nuclear station.

7. Due to its great ease of taking up and throwing off the load, hydropower can be used as the ideal spinning reserve in a system mix of thermal, hydro, and nuclear power stations.

8. Modern hydro-generators give high efficiency over a considerable range of load. This helps in improving the system efficiency.

9. Hydro-plants provide ancillary benefits like irrigation, flood control, afforestation, navigation, and aqua-culture.

10. Being simple in design and operation, the hydro-plants do not require highly skilled workers. Manpower requirement is also low.

Disadvantages of Water Power

1. Hydro-power projects are capital-intensive with a low rate of return. The annual interest of this capital cost is a large part of the annual cost of hydropower installations.

2. The gestation period of hydro projects is quite large. The gap between the foundation and completion of a project may extend from ten to fifteen years.

3. Power generation is dependent on the quantity of water available, which may vary from season to season and year to year. If the rainfall is in time and adequate, then only the satisfactory operation of the plant can be expected.

4. Such plants are often far away from the load center and require long transmission lines to deliver power. Thus the cost of transmission lines and losses in them are more.

5. Large hydro-plants disturb the ecology of the area, by way of deforestation, destroying vegetation and uprooting people. Strong public opinion against. The erection of such plants is a deterrent factor. The emphasis is now more on small, mini and micro hydel stations.

Hydroelectric power plant in India

Srisailam Hydel power plant – AP – 770 MW

Upper sileru Hydor electric project – AP – 120

Kodayar hydro electric power plant – TN – 100 MW

Iddiki hydel project – Kerala – 800 MW

THERMAL POWER GENERATION PLANT OR THERMAL POWER STATION

A thermal power generation plant or thermal power station is the most conventional source of electric power. The thermal power plant is also referred to as a coal thermal power plant and steam turbine power plant.

Let's dive into how a thermal power plan works.

Theory of Thermal Power Station

The theory of **thermal power stations** or the **working of the thermal power stations** is very simple. A **power generation plant** mainly consists of alternator runs with help of a steam turbine. The steam is obtained from high-pressure boilers.

Generally in India, bituminous coal, brown coal, and peat are used as fuel for the boiler. The bituminous coal is used as boiler fuel has volatile matter from 8 to 33% and ash content 5 to 16%. To increase thermal efficiency, coal is used in the boiler in powder form.

In a **coal thermal power plant**, the steam is produced at high pressure in the steam boiler due to the burning of fuel (pulverized coal) in boiler furnaces. This steam is further supper heated in a superheater.

This superheated steam then enters into the turbine and rotates the turbine blades. The turbine is mechanically so coupled with an alternator that its rotor will rotate with the rotation of turbine blades.

After entering in turbine the steam pressure suddenly falls and the corresponding volume of the steam increases.

After imparting energy to the turbine rotor, the steam passes out of the turbine blades into the condenser.

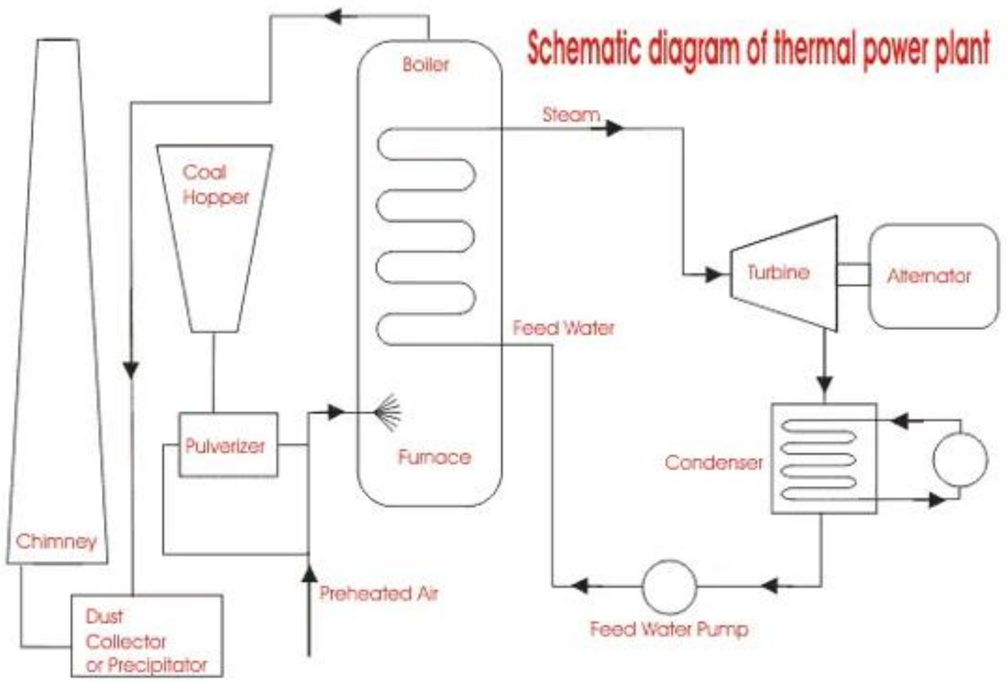
In the condenser, the cold water is circulated with the help of a pump which condenses the low-pressure wet steam.

This condensed water is further supplied to a low-pressure water heater where the low-pressure steam increases the temperature of this feed water; it is again heated at high pressure.

For better understanding, we furnish every step of the function of a **thermal power station** as follows,

1. First, the pulverized coal is burnt into the furnace of steam boiler.
2. High-pressure steam is produced in the boiler.
3. This steam is then passed through the superheater, where it further heated up.
4. This super heated steam is then entered into a turbine at high speed.
5. In turbine, this steam force rotates the turbine blades that means here in the turbine the stored potential energy of the high pressured steam is converted into mechanical energy.

Line Diagram of Power Plant



1. After rotating the turbine blades, the steam has lost its high pressure, passes out of turbine blades, and enters into a condenser.
2. In the condenser, the cold water is circulated with help of a pump which condenses the

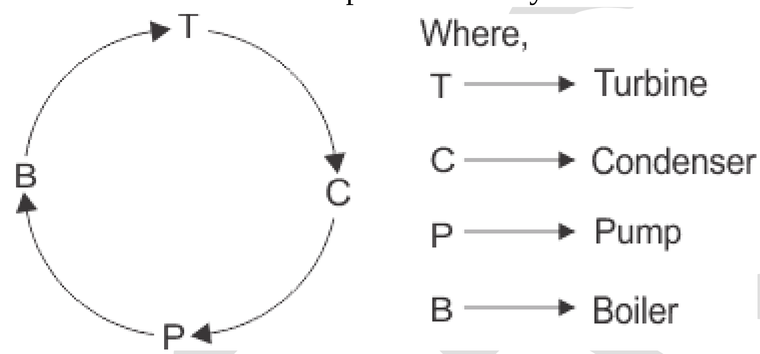
low-pressure wet steam.

3. This condensed water is then further supplied to a low-pressure water heater where the low-pressure steam increases the temperature of this feed water, it is then again heated in a high-pressure heater where the high pressure of steam is used for heating.

4. The turbine in the thermal power station acts as a prime mover of the alternator.

Overview of Thermal Power Plant

A typical Thermal Power Station Operates on a Cycle which is shown below.



The working fluid is water and steam. This is called the feed water and steam cycle. The ideal Thermodynamic Cycle to which the operation of a **Thermal Power Station** closely resembles is the rankine cycle.

In a steam boiler, the water is heated up by burning the fuel in the air in the furnace, and the function of the boiler is to give dry superheated steam at the required temperature. The steam so produced is used in driving the steam Turbines.

This turbine is coupled to the synchronous generator (usually a three-phase synchronous alternator), which generates electrical energy.

The exhaust steam from the turbine is allowed to condense into the water in the steam condenser of turbine, which creates suction at very low pressure and allows the expansion of the steam in the turbine to very low pressure.

The principal advantages of the condensing operation are the increased amount of energy extracted per kg of steam and thereby increasing efficiency, and the condensate which is fed into the boiler again reduces the amount of fresh feed water.

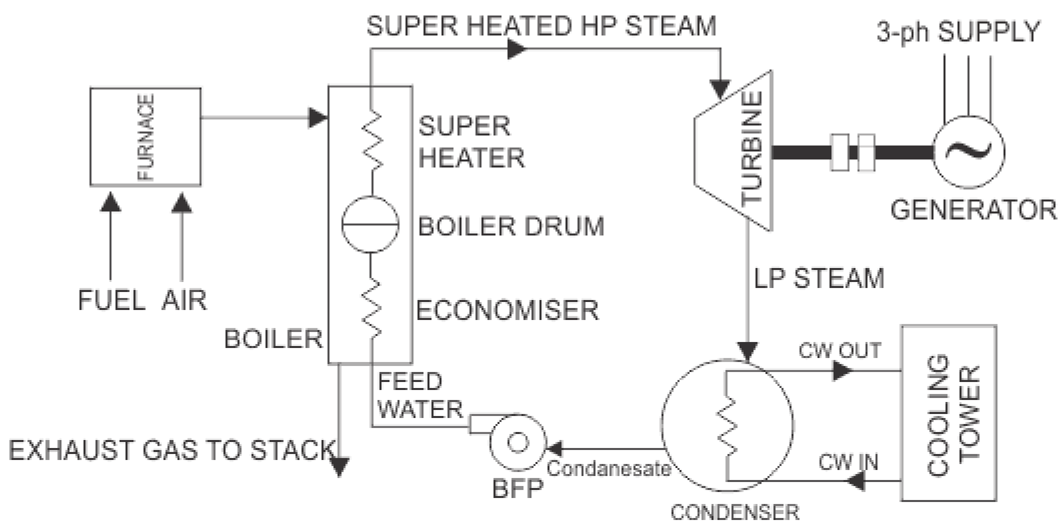
The condensate along with some fresh makeup feed water is again fed into the boiler by a pump (called the boiler feed pump).

In the condenser, the steam is condensed by cooling water. Cooling water recycles through the cooling tower. This constitutes a cooling water circuit.

The ambient air is allowed to enter the boiler after dust filtration. Also, the flue gas comes out of the boiler and gets exhausted into the atmosphere through stacks. These constitute air and flue gas circuits.

The flow of air and also the static pressure inside the steam boiler (called draught) is maintained by two fans called **Forced Draught (FD)** fan and **Induced Draught (ID)** fan.

The total scheme of a typical thermal power station along with different circuits is illustrated below.



Inside the boiler, there are various heat exchangers, viz. **Economizer**, **Evaporator** (not shown in the fig above, it is basically the water tubes, i.e. downcomer riser circuit), **Super Heater** (sometimes **Reheater**, **air preheater** are also present).

In Economiser the feed water is heated to a considerable amount by the remaining heat of flue gas.

The Boiler Drum maintains a head for natural circulation of a two-phase mixture (steam + water) through the water tubes.

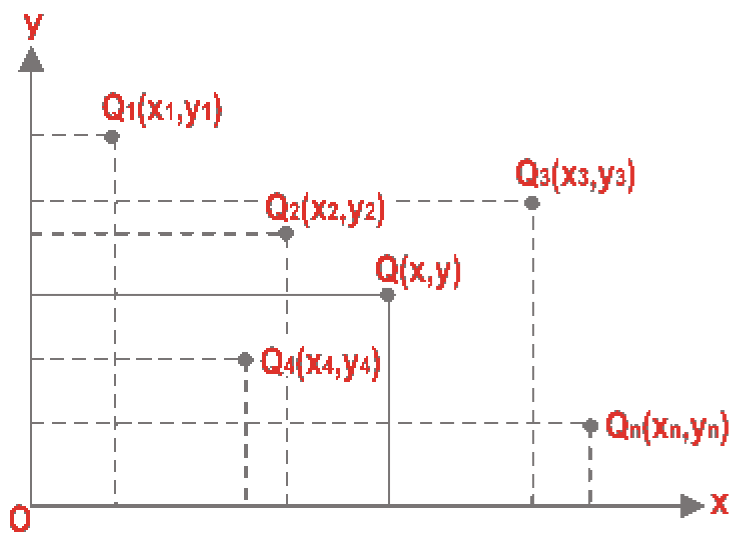
There is also a Super Heater which also takes heat from flue gas and raises the temperature of steam as per requirement.

The efficiency of Thermal Power Station or Plant

The overall efficiency of the steam power plant is defined as the ratio of heat equivalent of electrical output to the heat of combustion of coal. The overall efficiency of a **thermal power station** or plant varies from **20%** to **26%** and it depends upon plant capacity.

Installed plant capacity	Average overall thermal efficiency
upto 1MW	4%
1MW to 10MW	12%
10MW to 50MW	16%
50MW to 100MW	24%
above 100MW	27%

Thermal Power Plant Location



Determination of Load Center

A thermal power station or thermal power plant has an ultimate target to make a business profitable. Hence for optimizing the profit, the location of the station is much important factor.

Power generation plant location plays an optimizing part in the economy of the station.

The most economical location of a power plant can be determined by the graphical method as described below,

The most economical and ideal power plant location is the center of gravity of the load because for such a power generation plant the length of the power transmission network will be minimum, thus the capital cost to the system is reduced. Let's explain the graphical method, say, X and Y be two reference axes. Let's $Q_1(x_1, y_1)$, $Q_2(x_2, y_2)$, $Q_3(x_3, y_3)$, $Q_4(x_4, y_4)$,……………………………………….and $Q_n(x_n, y_n)$ are n numbers of load centers.

From the above graph we get, the coordinates of the center of gravity of the load, Q(x, y) where

$$x = \frac{x_1Q_1 + x_2Q_2 + x_3Q_3 + \ldots\ldots\ldots + x_nQ_n}{Q_1 + Q_2 + Q_3 + \ldots\ldots\ldots + Q_n}$$

$$\& \quad y = \frac{y_1Q_1 + y_2Q_2 + y_3Q_3 + \ldots\ldots\ldots + y_nQ_n}{Q_1 + Q_2 + Q_3 + \ldots\ldots\ldots + Q_n}$$

The location of the thermal power station is best at the center of gravity of the load, but many times it is not possible to establish a thermal power plant at the CG of the load.

Since normally CG point of the load may be at the heart of the city. So other points are to be considered to decide the best-optimized location of the power plant.

1. The **electric power generation plant** must be constructed at such a place where the cost of land is quite reasonable.
2. The land should be such that the acquisition of private property must be minimum.
3. A large quantity of cooling water is required for the condensers etc of **thermal power generation plant**, hence the plant should preferably be situated beside the big source of a natural water source such as a big river.
4. Availability of a huge amount of fuel at a reasonable cost is one of the major criteria for choosing a plant location.
5. The plant should be established on plane land.
6. The soil should be such that it should provide a good and firm foundation of plants and buildings.
7. The **thermal power plant** location should not be very nearer to the dense locality as

there is smoke, noise steam, water vapors, etc.

8. There must be ample scope of development of future demand.
9. A place for an ash handling plant for thermal power stations should also be available very nearby.
10. A very tall chimney of power station should not obstruct the traffics of airships.

Advantages of Thermal Power Station

The advantages of a thermal power station include:

1. Economical for low initial cost other than any generating plant.
2. Land required less than hydropower plant.
3. Since coal is the main fuel and its cost is quite cheap than petrol/diesel so generation cost is economical.
4. Maintenance is easier.
5. Thermal power plants can be installed in any location where transportation and bulk of water are available.

Disadvantages of Thermal Power Station

The disadvantages of a thermal power station include:

1. The running cost for a thermal power station is comparatively high due to fuel, maintenance, etc.
2. A large amount of smoke causes air pollution. The thermal power station is responsible for Global warming.
3. The heated water that comes from the thermal power plants has an adverse effect on the aquatic lives in the water and disturbs the ecology.
4. The overall efficiency of the thermal power plant is low like less than 30%.

NUCLEAR POWER STATION AND POWER PLANT

A Nuclear Power Plant is a Thermal Power station in which the heat source is Nuclear Reactor.

Nuclear Power Plant Introduction:

The cheap and abundant power is essential to the modern world in the coming years.

The repeated increase in industry and living standard of the people creates pressure on conventional sources of power, therefore, Coal Oil and Gas.

These sources will soon be unable to meet the increasing demand of the world.

The adoption of nuclear energy for the generation of power is Inevitable to the nation where other sources of generation are inadequate.

One of the outstanding facts about nuclear power is the largest amount of energy that can be released from a small mass of active materials.

The complete fission of 1 kg of Uranium contains the energy equivalent to 3100 tons of coal or 1700 tons of oil.

The nuclear power is not only available in evidence but it is cheaper than the power generated by conventional sources. As of 2013 in India, there are 6 nuclear power plants available with 20 Nuclear reactors generating 4800-megawatt power.

India has planned to increase nuclear power generation by more than 30%of present generations by 2050.

Nuclear Power Plant Definition :

A nuclear power plant is a facility that converts atomic energy into usable power. The heats produced by a reactor is generally used to drive a turbine which in turn drives an electric generator.

Nuclear Plant Overview:

A nuclear power plant is a type of power station that generates electricity using heat from nuclear reactions.

These reactions take place within a reactor.

The plant also has machines that remove heat from the reactor to operate a steam turbine and generator to make electricity.

The electricity made by nuclear power plants is also called nuclear power.

Nuclear power plants are usually near water to remove the heat the reactor makes.

Some nuclear power plants use cooling towers to do this.

Nuclear power plants use uranium as fuel.

When the reactor is on, uranium atoms inside the reactor split into two smaller atoms.

When uranium atoms split, they give off a large amount of heat. This splitting of atoms is called fission.

The most popular atoms to fission are uranium and plutonium.

Those atoms are slightly radioactive. The atoms produced when fuel atoms break apart are strongly radioactive.

Today, fission only happens in nuclear reactors.

In nuclear reactors, fission only happens when the reactor's parts are arranged properly.

Nuclear power plants turn their reactors off when replacing old nuclear fuel with new fuel.

Nuclear Power Plants in World:

There are about four hundred nuclear power plants in the world, with many in the United States, France, and Japan.

Some famous accidents at nuclear power plants were the 2011 Fukushima nuclear disaster in Japan,

1986 Chernobyl disaster in Ukraine, and

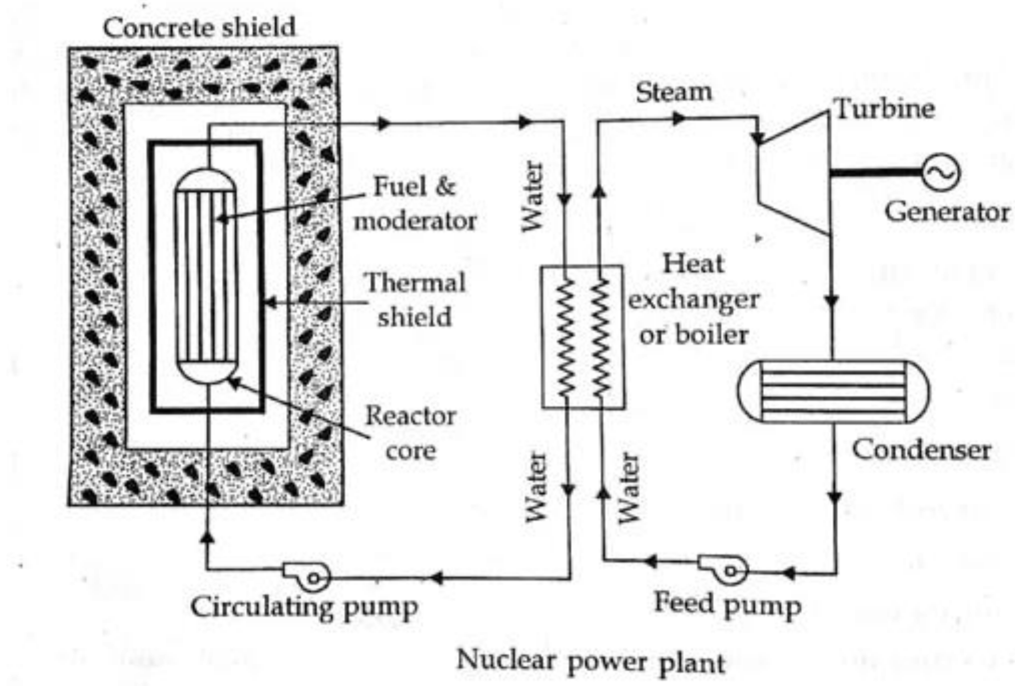
1979 Three Mile Island accident in the United States.

An Anti-nuclear movement in Australia opposes the making of any nuclear power plants in the country.

Nuclear Reaction:

In simple words, the Nuclear Reaction is like Splitting the main atoms which release Kinetic energy and Further used for Power Generation (Here several steps occurs).

Nuclear Power Plant Layout:



Nuclear power plant

The above figure shown is the general layout of the Nuclear Power plant.

In brief, The working of Nuclear Power Plant, As you can see there is a **Concrete shield (**Here Uranium atoms are bombarding to produce enough amount of heat**)** that heats comes to contact with water and water gets heated and converted into steam and

Now from heat ex-changer device the steam sends to the turbine for rotating blades and generating Electricity with the use of Generator and Some amount of steam which is not used comes through the condenser where it loses the heat property and goes to the heat exchanger and then again water sends to Concrete shield for repeating the process.

I know you are curious to learn how the main parts work? Explained below:

Nuclear Power Plant Main Parts or Component:

The Nuclear Power Plant consists of 7 Main Parts:

- ***Nuclear Reactor***
- ***Coolant circulating pump***
- ***Heat Exchanger***
- ***Feed pump***
- ***Condenser***
- ***Turbine and***
- ***Generator***

Nuclear Reactor:

The nuclear reactors are used at nuclear power plants for the generation of electricity and in nuclear marine propulsion.

The Heat generates from nuclear fission is passed to a working fluid which is (water or gas), which in turn runs through steam turbines.

These either drive a ship's propellers or turn electrical generators' shafts.

Nuclear generated steam can be used for industrial process heat and some reactors are used to produce isotopes for medical and industrial use, or production of weapons-grade plutonium.

Coolant Circulating pump:

It circulates the water which is further going to be heated and used for turbine blade rotating.

Heat Exchanger:

The name itself indicates the Heat exchanger which works is to exchange the heat from lower to higher.

Feed pump:

Send the water from condenser to heat exchanger and from there by the use of a circulating pump it sends to the concrete shield system.

Condenser:

The condenser is the component that is used for extracting the heat from the working fluid or in simple you can say it cools the working fluid because it is having a low temperature.

Turbine:

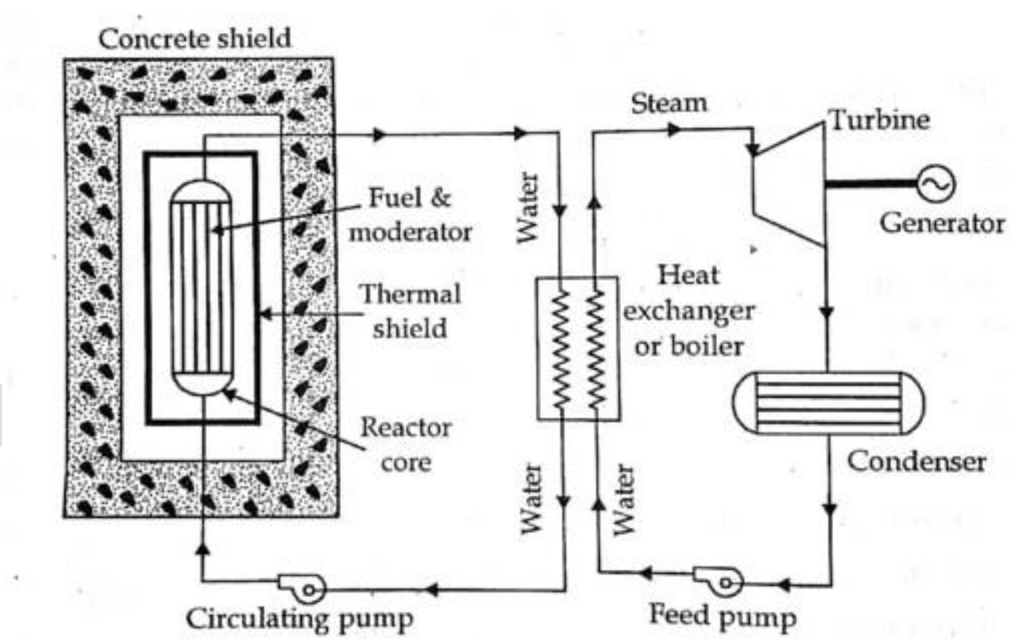
The turbine is a device that is used for power generation.

Here The fluid strikes to turbine blade which is further converted Kinetic energy into mechanical energy and generator convert that mechanical energy into electrical energy.

Generator:

The generator is further used for converting into Electrical energy and the output we got is Power.

How Nuclear Power Plant Diagram Works?



Nuclear power plant

The working of Nuclear Plant: Nuclear Plant consists of the ***Nuclear Reactor, Coolant circulating pump, Heat Exchanger, Feed Pump, Condenser, Turbine, and Generator.***

The Heat is generated in a reactor by the fission reaction.

The coolant in the primary circuit gets heated by observing the heat and enters into the Heat Exchanger.

Here, In the Heat Exchanger, the feed water is heated and converted into the steam by the hot coolant using heat transfer.

The steam from the Heat Exchanger will enter in the turbine to rotate turbine blades and generates power.

The steam after doing the work enters into the condenser and converted into the water which is pumped again to the Heat Exchanger by the feed pump.

The hot coolant gets cold in the Heat Exchanger is recirculated into the reactor by the coolant circulating pump.

The cycle is repeated continuously for the generation of power.

Nuclear Power Plant Advantages:

There are some advantages of Nuclear Plant:

- *Nuclear Power Plant requires less space as compared to other Power plants.*
- *Well suited for large demands.*
- *It gives better performance at high load factor 80 to 90%.*
- *Less fuel consumption and no fuel handling.*
- *The transportation cost of fuel is very less.*
- *Increased reliability of operation.*
- *Power plants not affected by adverse weather conditions.*
- *Water required is less.*
- *The high capacity of the plant can be installed.*
- *Compact and simple in maintenance.*

Nuclear Power Plant Disadvantages:

There are some disadvantages of Nuclear Plant:

- *Nuclear Power Plant has a High initial cost.*

- *The danger of radioactivity hazards is always persisting.*
- *Not suitable for varying load conditions.*
- *The disposal of fission products is a big problem.*
- *The maintenance cost is always higher.*
- *Working condition is always detrimental to the health of the workers.*

Nuclear Power Plant Application:

These are the application of Nuclear Plant:

1. *Nuclear Power plant for generating a good amount of electricity-*
2. *Nuclear energy now provides about 11% of the world's electricity from about 450 power reactors.*
3. *The main use of nuclear energy is the production of electric energy. Nuclear power plants are responsible for generating electricity.*
4. *The energy Thermal is obtained which will be transformed into mechanical energy and then later into electrical energy.*

Nuclear Power Plant In India Location :

Having more than 10 Nuclear Power Plant exists in India. Some of them I have listed below which is:

1. Tarapur (Operator: Nuclear Power Corporation of India Limited (NPCIL)- Maharashtra)

2. Rawatbhata (Operator: Nuclear Power Corporation of India Limited (NPCIL)-Rajasthan)

3. Kudankulam (Operator: Nuclear Power Corporation of India Limited (NPCIL)-Tamil Nadu)

4. Kaiga (Operator: Nuclear Power Corporation of India Limited (NPCIL)-Karnataka)

5. Kakrapar (Operator: Nuclear Power Corporation of India Limited (NPCIL)-Gujarat)

6. Kalpakkam (Operator: Nuclear Power Corporation of India Limited (NPCIL)-Tamil Nadu)

7. Narora (Operator: Nuclear Power Corporation of India Limited (NPCIL)-Uttar Pradesh)

RENEWABLE ENERGY

What is Renewable Energy?

Renewable energy is an energy that is produced from natural processes and continuously replenished. Few examples of renewable energy are sunlight, water, wind, tides, geothermal heat, and biomass. The energy that is provided by renewable energy resources is used in 5 important areas such as air and water cooling/heating, electricity generation, the rural sector, and transportation.

According to a report in 2016 by REN21, the global energy consumption by the use of renewable energy resources contributed to 19.2% in 2014 and 23.7% in 2015. Many countries have started to invest in these renewable energy resources as these resources will help in maintaining sustainable development. The amount of investment in 2015 was about 286 billion dollars and major sectors were biofuel, solar power, wind, and hydroelectricity.

The existence of renewable energy resources is spread over to a wide geographical area in comparison to the conventional energy resources which are often concentrated to a limited number of countries like the oil and gas are mostly concentrated in the Middle East countries. The use of renewable energy resources in energy generation is resulting in less pollution and has a significant effect on economic benefits and energy security.

Examples of Renewable Energy

We can define renewable energy as those energies which can never be depleted. The importance of renewable energy is invaluable. These types of energy sources are different from fossil fuels, such as oil, coal, and natural gas. Some examples of renewable energy sources are:

- Wind energy
- Solar energy
- Geothermal energy
- Hydropower
- Biomass energy

Sources of Renewable Energy

The sources could sustain for a longer period of time and can easily be renewed often. Sustainable sources are biomass, nuclear power, geothermal, wind energy, solar power, tidal power, and wave power.

The sources of renewable energy are known to be less polluting and therefore the whole world is looking forward to new carbon emission norms, where carbon will play a major role in developing new factories and industries. They will be rated according to the carbon emission and the products that they are producing will be rated accordingly.

Types of Renewable Energy

1. **Solar Energy:** The radiant light and heat energy from the sun is harnessed with the use of solar collectors. These solar collectors are of various types such as photovoltaic, concentrator photovoltaic, solar heating, (CSP) concentrated solar power, artificial photosynthesis, and solar architecture. This collected solar energy is then used to provide light, heat, and different other forms of electricity.

2. **Wind Energy:** The energy we get from winds is known as wind energy. For this, windmills have been used for hundreds of years to pump out water from the ground. We use large tall wind turbines that allow winds to generate electricity. The natural airflow on the surface of the earth is used to run the wind turbines. The modern-day wind turbines range from about 600 Kilowatt to 5 Megawatts, for commercial purposes these are rated with an output power of 1.5 to 3 Megawatts. The most preferred locations for these wind turbines to be installed are the areas which and strong and have constant airflows on offshore and sites that are at high altitudes. The power generated from wind energy in 2015 met 4% of global energy consumption.

3. **Hydroelectricity:** According to statistics, hydroelectricity generated around 16.6% of the global energy resources and constituted about 70% of all the renewable electricity. This energy is another alternative source of energy that is generated by the construction of dams and reservoirs on the flowing water, the kinetic energy from the flowing water is used to run the turbines which generate electricity. Tidal power converts the energy of tides and Wave power which captures the energy from the surface of the ocean waves for power generation. These two forms of hydropower also have huge potential in electric

power generation

4. **Geothermal Energy:** It is the energy that is generated from the thermal energy which is stored in the earth. The heat energy is captured on sources such as hot springs and volcanoes and this heat is directly used by industries for heating the water and other purposes.

5. **Bio Energy:** This type of energy is derived from the biomass which is a type of biological material derived from living organisms and plant-derived materials which are called lingo-cellulosic biomass. Biomass can be directly used via combustion to produce heat and indirectly it can be used to convert to biofuels. Biomass can be converted to other usable forms of energy such as transportation fuels like ethanol, biodiesel, and methane gas.

ELECTRICAL POWER TRANSMISSION SYSTEM

Electrical energy, after being produced at generating stations (TPS, HPS, NPS, etc.) is transmitted to the consumers for utilization. This is due to the fact that generating stations are usually situated away from the load centers. The network that transmits and delivers power from the producers to the consumers is called the **transmission system**. This energy can be transmitted in AC or DC form. Traditionally, AC has been used for years now, but HVDC (High Voltage DC) is rapidly gaining popularity.

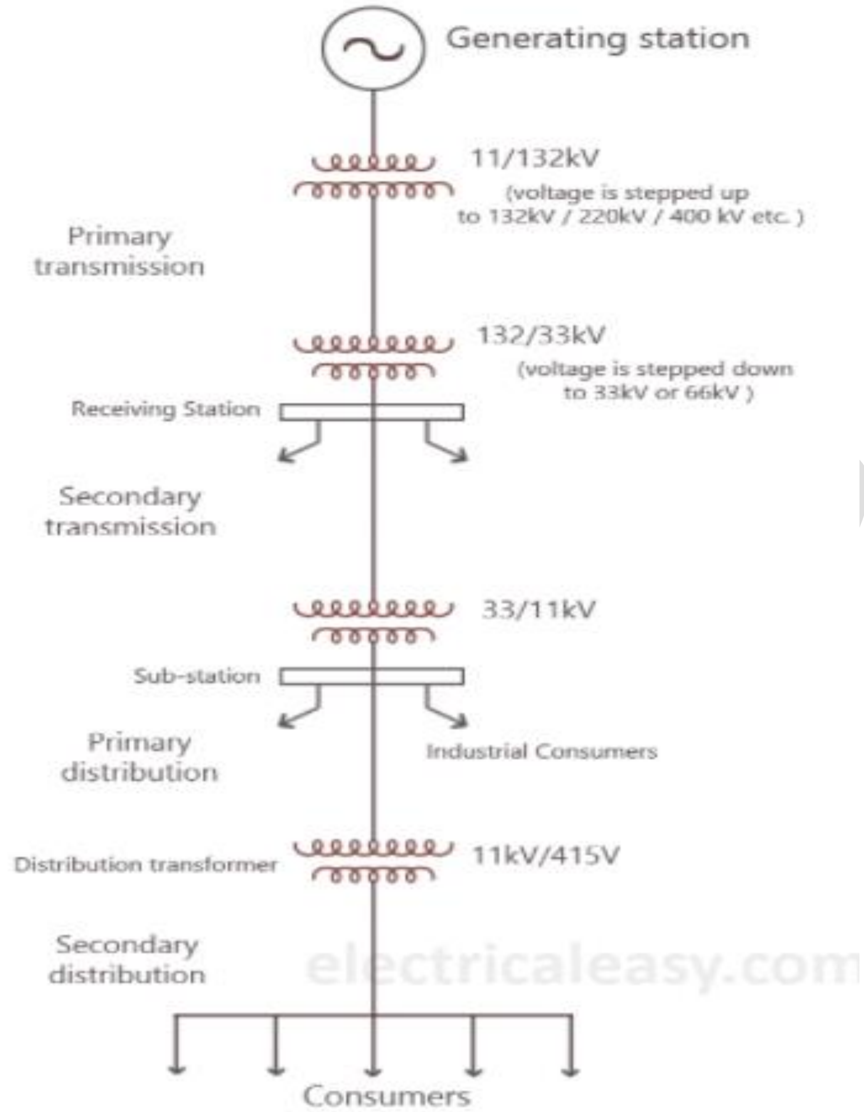
Single Line Diagram Of AC Power Transmission System

A typical single line diagram that represents the flow of energy in a given power system is shown below:

Electric power is commonly (or usually) generated at 11 kV in generating stations in India and Europe. While in some cases, generation voltage might be higher or lower. Generating machines, to be used in power stations, are available between 6 kV to 25 kV from some big manufacturers. This generating voltage is then stepped up to 132kV, 220kV, 400kV or 765kV etc. Stepping up the voltage level depends upon the distance at which power is to be transmitted. Longer the distance, higher will be the voltage level. Stepping up of voltage is to reduce the I^2R losses in **transmitting the power** (when voltage is stepped up, the current reduces by a relative amount so that the power remains constant, and hence I^2R loss also reduces). This stage is called as **primary transmission**.

The voltage is the stepped down at a receiving station to 33kV or 66kV. **Secondary transmission** lines emerge from this receiving station to connect substations located near load centers (cities etc.).

The voltage is stepped down again to 11kV at a substation. Large industrial consumers can be supplied at 11kV directly from these substations. Also, feeders emerge from these substations. This stage is called as **primary distribution**.



Feeders are either overhead lines or underground cables which carry power close to the load points (end consumers) up to a couple of kilometers. Finally, the voltage is stepped down to 415 volts by a pole-mounted distribution transformer and delivered to the distributors. End consumers are supplied through a service mains line from distributors. The **secondary distribution** system consists of feeders, distributors and service mains.

Different Types Of Transmission Systems

1. Single phase AC system
   - single phase, two wires
   - single phase, two wires with midpoint earthed
   - single phase, three wires
2. Two phase AC system
   - two-phase, three wires
   - two-phase, four wires
3. Three phase AC system
   - three-phase, three wires
   - three-phase, four wires
4. DC system
   - DC two wires
   - DC two wires with midpoint earthed
   - DC three wires

Electric power transmission can also be carried out using underground cables. But, construction of an underground transmission line generally costs 4 to 10 times than an equivalent distance overhead line. However, it is to be noted that, the cost of constructing underground transmission lines highly depends upon the local environment. Also, the cost of conductor material required is one of the most considerable charges in a transmission system. Since conductor cost is a major part of the total cost, it has to be taken into consideration while designing. The choice of transmission system is made by keeping in mind various factors such as reliability, efficiency and economy. Usually, overhead transmission system is used.

Main Elements Of A Transmission Line

Due to the economic considerations, three-phase three-wire overhead system is widely used for electric power transmission. Following are the main elements of a typical power system.

- **Conductors:** three for a single circuit line and six for a double circuit line. Conductors must be of proper size (i.e. cross-sectional area). This depends upon its current capacity. Usually, ACSR (Aluminium-core Steel-reinforced) conductors are used.

- **Transformers:** Step-up transformers are used for stepping up the voltage level and step-down transformers are used for stepping it down. Transformers permit power to be transmitted at higher efficiency.
- **Line insulators:** to mechanically support the line conductors while electrically isolating them from the support towers.
- **Support towers:** to support the line conductors suspending in the air overhead.
- **Protective devices:** to protect the transmission system and to ensure reliable operation. These include ground wires, lightening arrestors, circuit breakers, relays etc.
- **Voltage regulators:** to keep the voltage within permissible limits at the receiving end.

PRIMARY AND SECONDARY TRANSMISSION AND DISTRIBUTION NETWORKS

Generally, a power system consists of the following stages:

- Power Station.
- Primary Transmission.
- Secondary Transmission.
- Primary Distribution.
- Secondary Distribution.

Power Station

The electric power is generated at the power station by 3-phase, 3-wire system employing the number of alternators in parallel. The generation voltages are 3.3, 11, or 33 kV; however, the most common value adopted in practice is 11 kV. At the power station, the generation voltage (11 kV) is stepped up to 132, 220, or 400 kV (i.e., whichever is economical) depending upon the distance; the amount of power to be transmitted and the system stability.

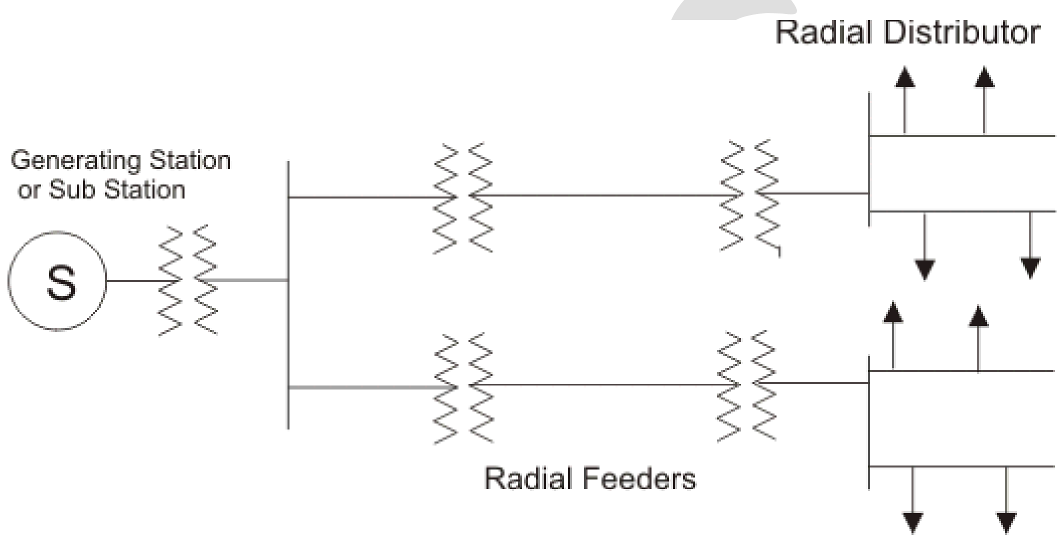
Primary Transmission System

The bulk of electrical power is transmitted from the generating station to the load centers (i.e., main sub-stations) by overhead lines at 132, 220 or 400 kV. This forms the **primary transmission system**. For primary transmission 3-phase, 3-wire system is always employed, and the aluminum conductors with steel reinforcement (ACSR) are run over the steel towers.

Secondary Transmission System

On the outskirt of cities, there are substations where power is received at 132, 220, or 400kV and is stepped down to 66 or 33kV depending upon the amount of power to be fed to a particular area. Then the power is transmitted at 66 or 33kV by overhead lines. This constitutes the **secondary transmission system**. Three-phase, three-wire system is always employed.

Primary Distribution System



Primary distribution systems consist of feeders that deliver power from distribution substations to distribution transformers. A feeder usually begins with a feeder breaker at the distribution substation. Many feeders leave substation in a concrete ducts and are routed to a nearby pole.

Primary distribution system is of four types-

1. Radial feeder

2. Parallel feeder

3. Loop feeder

4. Primary network

1. Radial feeder

Radial feeder system is main types of primary distribution system

This feeder is used to supply small and medium residential, commercial loads. It radiates from the secondary substation and branches into sub feeder and laterals which extended into all parts of service area. The feeder and sub feeder are three phase three wire circuit. The distribution transformer is connected to primary feeder, sub feeder and laterals through fused cutouts.

2. Parallel feeder

It consists of duplicate feed system having two radial feeders running in parallel. Each feeder supplies about half of total load of the area but has a capability to supply the entire load in the event of an outage on the other feeder. Failure of any feeder will result interruption of service until the load normally supplied by the faulted feeder is transferred to the other feeder by automatic control switch.

3. Loop feeder

A system of two or more radial feeders originating from the same or secondary different substation and separately routed through load area is known as loop feeder.it is also main types of primary distribution system.

If ends of two feeders are tied together through normally open switching device the resulting arrangement is known as open loop system and if ends are tied together by means of normally closed switching device the result is a ring loop feeder.

4. Primary Network

This system consists of a number of interconnected feeders. Two or more secondary transmission circuit supply two or more secondary substations from which the feeder takes off. Because the feeder is interconnected power is supplied to all the distribution transformers even though a part of network may be out of service. Each secondary substation consists of a transformer and the necessary switch gear to isolate the faulty feeder and to control feeder.

Secondary distribution system

The secondary distribution system consist of three phase four wire 400V distributors laid along road sides. The service connection are tapped off the off the distributors at convenient points. These connection may be 1 phase two wire circuit or 3 phase 4 wire circuit.These are basic types of primary distribution system.

Secondary distribution system

The secondary system used are-

1. Radial

2. Open loop

3. Network distribution

1. Radial system

It takes off from the distribution transformer and runs through the area to be served by it.

2. Open loop system

This system consist of two distributors taking off from the same distribution transformer and running in different directions and supplying different areas at time of fault one of distributors, power can supplied through partially, from the other distributor.

3. Network distribution

A network grid system consist of a number of inter connected distributors. Two or more distribution transformers feed the distribution network and operate continuously in parallel. This system is suitable for serving high load density metropolitan areas. Which are shows in secondary distribution system.

MODULE V

TRANSFORMERS AND ELECTRICAL MACHINES

TRANSFORMERS

INTRODUCTION

A transformer is one of the most common devices found in electrical system that links the circuits which are operating at different voltages .These are commonly used in applications where there is a need of AC voltage conversion from one voltage level to another.

It is possible either to decrease or increase the voltage and currents by the use of transformer in AC circuits based on the requirements of the electrical equipment or device or load. Various applications use wide variety of transformers including power, instrumentation and pulse transformers.

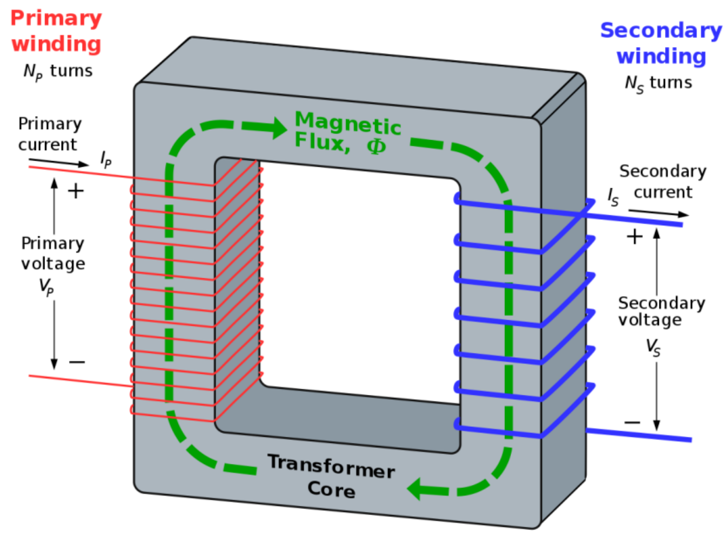
In a broad, transformers are categorized into two types, namely, electronic transformers and power transformers. Electronic transformers operating voltages are very low and are rated at low power levels. These are used in consumer electronic equipments like televisions, personal computers, CD/DVD players, and other devices.

The term power transformer is referred to the transformers with high power and voltage ratings. These are extensively used in power generation, transmission, distribution and utility systems to increase or decrease the voltage levels. However, the operation involved in these two types of transformers is same. So let us go in detail about the transformers.

What is an Electric Transformer?

A transformer is a static device (means that has no moving parts) that consists of one, two or more windings which are magnetically coupled and electrically separated with or without a magnetic core. It transfers the electrical energy from one circuit to the other by electromagnetic induction principle.

The winding connected to the AC main supply is called primary winding and the winding connected to the load or from which energy is drawn out is called as secondary winding. These two windings with proper insulation are wound on a laminated core which provides a magnetic path between windings.



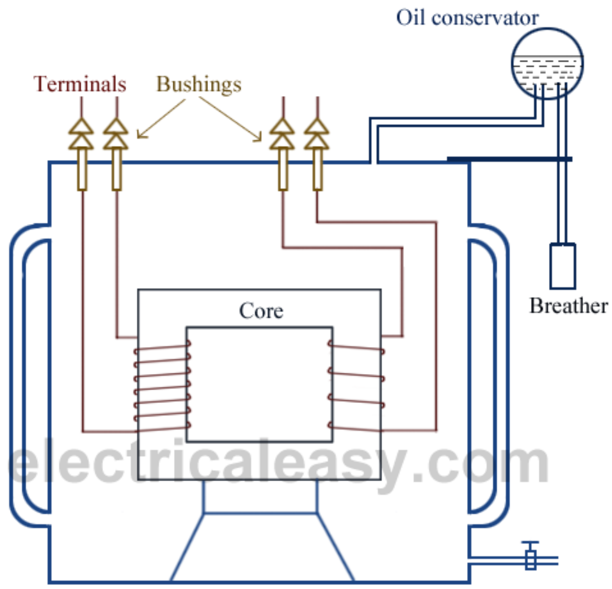
electric transformer

When the primary winding is energized with alternating voltage source, an alternating magnetic flux or field will be produced in the transformer core. This magnetic flux amplitude depends on the applied voltage magnitude, frequency of the supply and the number of turns on the primary side.

This flux circulates through the core and hence links with the secondary winding. Based on the principle of electromagnetic induction, this magnetic linking induces a voltage in the secondary winding. This is called as mutual induction between two circuits. The secondary voltage depends on the number of turns on the secondary as well as magnetic flux and frequency.

Transformers are extensively used in electrical power systems to produce the variable values of voltage and currents at the same frequency. Therefore , by an appropriate primary and secondary turns proportion desired voltage ratio is obtained by the transformer.

BASIC CONSTRUCTION OF TRANSFORMER



The main parts of a transformer are core, windings, container or tank, bushings and conservator and radiators.

Core

For high power applications, transformer core is made with high permeability material which provides the low reluctance path for the magnetic flux. The cross section of the core would be square or rectangular.

Generally the iron core transformers provide better power transformation compared with air core transformers. Air core transformers are used for high frequency application (above 2 KHz) whereas , for low frequency applications (below 2 KHz) iron core transformers are employed.

In all types of transformers, core is made up of silicon steel or sheet steel laminations which are assembled to provide a continuous magnetic path for the flux. With this laminated core eddy current losses are minimized.

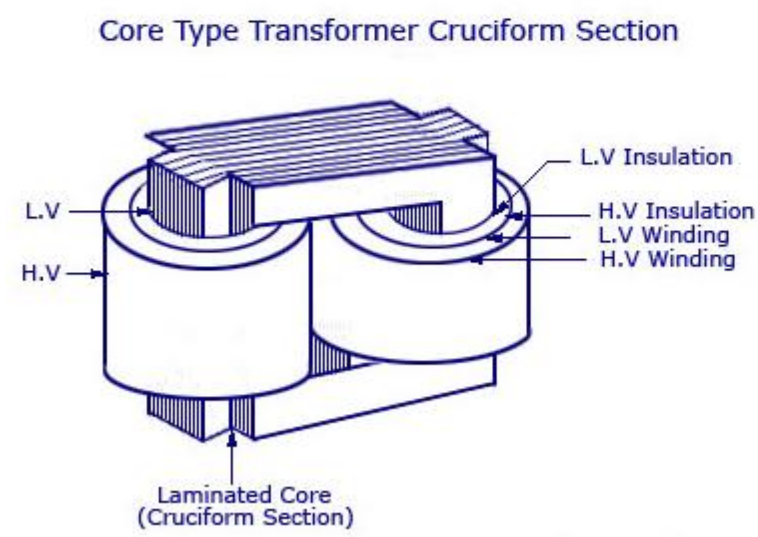
The thickness of these laminated sheets of steel are 0.35 to 5 mm and are insulated with a varnish, or oxide, or phosphate and then formed as a core.

For a better magnetic properties, Hot rolled grain oriented (HRGO) steel, or Cold Rolled Grain

Oriented (CRGO) steel, or High B (HiB) laminations are used. In case of small transformers, core is constructed with hot rolled silicon steel laminations in the form of E and I, C and I or O are used.

Based on the construction, transformers are classified into two types in the manner in which the windings are placed around the core. These types are core and shell type transformers.

Core Type transformer



core type transformer

In this type of transformer, windings surround the considerable part of the core. Generally, distribution transformers are of core type. Some of the large power transformers are of shell type.

Form-wound, cylindrical coils are used in the core type transformers and these coils may be rectangular, or oval, or circular. For small size core type transformer, a simple rectangular core with a cylindrical coil in either circular or rectangular form is used.

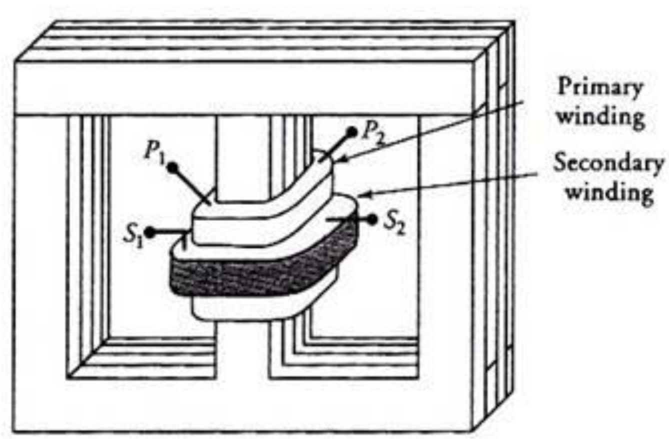
And for a large sized core type transformer, cruciform core with round or circular cylindrical coils are used. In most of the core type transformers, cylindrical coils are used due to their mechanical strength. These cylindrical coils are wound in helical layers and are insulated from each other by insulating materials like cloth, paper, mica, etc.

It is easy to insulate the LV winding compared to the HV winding; hence it is placed nearer to the core.

Shell Type Transformer

In a shell type transformer, iron core surrounds a considerable portion of the copper winding as a reverse case to the core type transformer. In this type also, coils are former wound, but are of multilayer disc type coils which are wounded in the form of pancakes. These multilayer disc coils in different layers of are separated each other by paper. The whole winding consists of stacked discs and in between the coils the insulation space is provided to form the horizontal insulating and cooling ducts.

Berry transformer is the most commonly used shell type transformer. In shell type, core has three limbs and the windings are wound around the central limb. Both LV and HV windings are divided into different coils which are arranged alternately. Between the LV windings, HV windings are sandwiched. Again to reduce the insulation requirement, LV windings are placed adjacent to the core. This type of construction is preferred for high rating transformers.



shell type transformer

Windings

Generally, the (two winding) transformer has two windings namely primary and secondary windings which are made up of high grade copper.

The insulated stranded conductors are used as windings for carrying high currents. This insulation avoids turns contacting with other turns.

The voltage connected to the primary winding is called primary voltage whereas the induced voltage in the secondary is called as secondary voltage. If the secondary voltage is more than the primary, it is called as step-up transformer and if less, it is called as step-down transformer. Therefore, the windings are designated as HV and LV windings based on the voltage level.

Compared to the LV winding, HV winding needs more insulation to withstand high voltages, also needs more clearance to the core and the body.

The transformer coils can be concentric or sandwiched coils. Concentric coils are used in core type transformers whereas sandwiched coils are used in shell type transformers. In concentric arrangement, LV winding is placed near to the core and HV winding is placed around the LV winding for low insulation and clearance requirements. The most commonly used coils for the transformer include helical, sandwiched, disc and cross over coils.

Tanks and Accessories

Other different parts and accessories are also fitted on the transformer for its efficient work as well as for longer life and better services of the transformer. They are as follows:

Conservator

The Conservator is a cylindrical tank placed on the top or on the roof of the main tank of the transformer. A large cover is provided which can be opened from time to time for the proper maintenance and cleaning of the transformer. It acts as a reservoir for the transformer insulating oil.

When the transformer is fully loaded and the temperature of the transformer rises high, an increase in the volume of the air inside the transformer takes place. As the level of the oil increases and decreases simultaneously, thus, a conservatory provides adequate space for this expanded oil inside the transformer.

Breather

As in the human body, there is a heart, similarly, a breather acts as a heart for the transformer. When the temperature of the transformer rises, the insulating oil in the transformer gets heated up. This oil expands and contracts.

When the oil heats up and expands, the transformer breaths air in and thus the oil gets cooled and the level of oil goes down and the air is absorbed in it. This process of taking air in and out is called breathing of the transformer.

The level of oil in the chamber increases and decreases when the breather takes the air in and out for cooling of the oil. This air carries moisture, which contaminates the oil and thus the quality of oil gets deteriorate.

For eliminating this moisture content, the breather is filled with Silica Gel. The main function of the silica gel is to separate moisture from the oil, maintaining the quality of the insulating oil. Initially, the color of the silica gel is blue and as it absorbs the moisture from the oil it turns into pink color.

Fresh Silica gel drys down the air to a dew point below **-40 degrees Celsius**.

Explosion Vent

The explosion vent is a thin aluminum pipe placed at both the ends of the transformer to prevent the transformer from the damage. When the temperature increases in the transformer drastically and the excessive pressure is created inside the transformer, the explosive vent helps in releasing the pressure.

Radiator

The main function of the radiator is to cool the oil in the transformer. The radiator is the detachable device whose upper and lower portion is connected by a valve to the transformer tank. When the transformer cleaning and maintenance are done the valve prevents the draining of the oil when the radiator is detached from the transformer.

When the transformer is in the working conditions, the oil of the transformer gets heated and moves up in the main tank and enters the radiator through the upper valve. There it gets cooled and from the lower valve of the radiating unit the oil again enters the transformer tank and this process continues.

Bushings

The Bushings in the transformer are the insulting device that allows an electrical conductor to pass electrical energy safely through it. It provides electrical field strength to the insulation of the conductors to withstand if a large amount of electric energy passes through it. **Solid porcelain** type bushing is used in smaller transformer and **oil-filled condenser** type bushing is used in large transformer.

The most common cause of the failure of the bushing resulting in damage to the transformer is the entrance of the moisture. The power factor of the bushing will always be in stable condition, but if the variation is seen in the power factor that means there is deterioration in the insulation.

This can be identified by the tests known as acceptance or routine test and Doble Power Factor Test.

Because of no moving parts, the efficiency of the transformer is very high which may vary from 95% to 98%.

WORKING PRINCIPLE OF TRANSFORMER

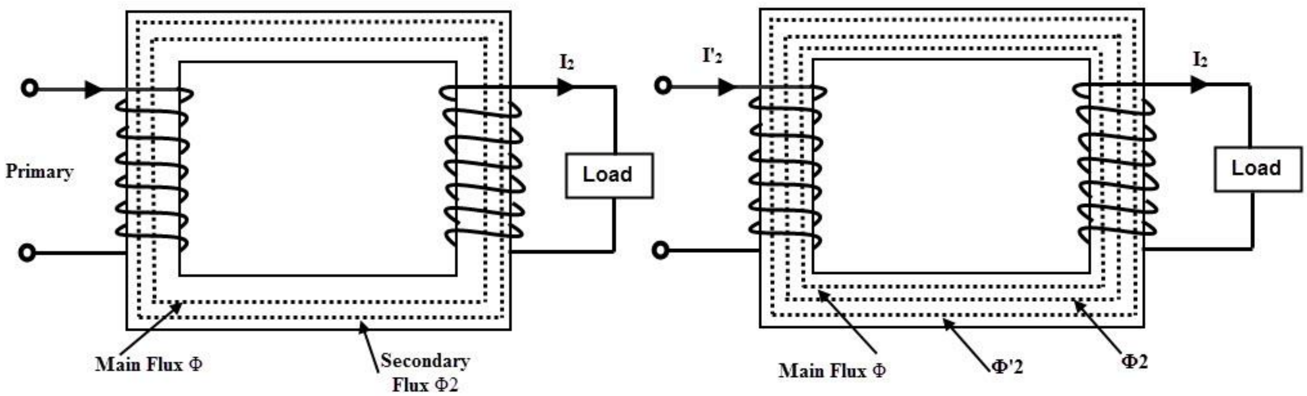
The operation of the transformer is based on the principle of mutual induction between two coils or winding which are linked by a common magnetic flux. When the primary winding is energized with AC source supply, a magnetic flux is established in the primary winding.

This flux is linked with both primary and secondary windings because the core provides a low reluctance path for the magnetic flux. Hence, most of the flux produced by the primary winding links with the secondary winding. This is called as main flux or useful flux. And also, the flux which does not link with the secondary winding is called as leakage flux. Most of the transformers are designed to have low leakage flux to reduce the losses.

According to the Faraday’s laws of electromagnetic induction, this flux linkage with both primary and secondary windings induces EMFs in them. This EMF induced in each winding is proportional to the number of turns in it. The voltage or EMF induced in the primary winding is called as back EMF which opposes the input supply voltage to the extent that no primary current would flow.

But small magnetizing current flows through the primary of the transformer. The EMF induced in the secondary winding is the open circuit voltage. If the secondary circuit is closed or the load is connected, secondary current starts flowing through it which causes to create demagnetizing magnetic flux. Due to this demagnetizing flux, the unbalance is created between the applied voltage and back EMF.

To restore the balance between these two, more current is drawn from the supply source so that equivalent magnetic field is created to balance with secondary field.



Since the same mutual flux cuts both windings, the EMF induced in the each turn of both windings are same. Hence the total induced EMF in each winding must be proportional to the number of turns in that winding. This turns out for the establishment of well-known relationship between induced EMF and the number of turns. And is given as

$$E1 / E2 = N1 / N2$$

Since the terminal voltages of the both windings are slightly different from their induced EMFs, we can write as

$$V1/V2 = N1/N2$$

This is called as the transformation ratio of the transformer. This transformation value is greater than unity in case of step-up transformer and less than unity in step-down transformer.

In terms of ampere turns balance,

$$I1N1 = I2N2$$

$$I1/I2 = N2/N1$$

EMF EQUATION OF TRANSFORMERS

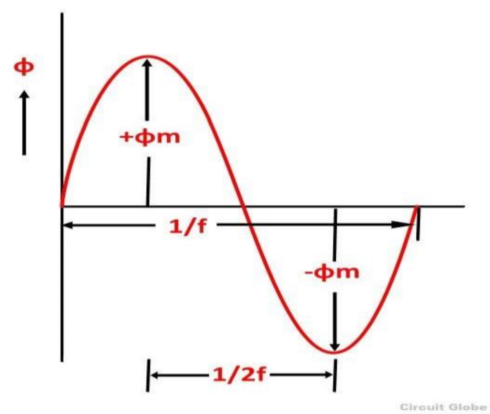
When a sinusoidal voltage is applied to the primary winding of a transformer, alternating flux ϕ_m sets up in the iron core of the transformer. This sinusoidal flux links with both primary and secondary winding. The function of flux is a sine function.

The rate of change of flux with respect to time is derived mathematically.

The derivation of the **EMF Equation** of the transformer is shown below. Let

- ϕ_m be the maximum value of flux in Weber
- f be the supply frequency in Hz
- N_1 is the number of turns in the primary winding
- N_2 is the number of turns in the secondary winding

Φ is the flux per turn in Weber



As shown in the above figure that the flux changes from + ϕ_m to – ϕ_m in half a cycle of 1/2f seconds.

By Faraday's Law

Let E_1 be the emf induced in the primary winding

$$E_1 = -\frac{d\psi}{dt} \ldots\ldots\ldots (1)$$

Where $\Psi = N_1\phi$

$$\text{Therefore, } E_1 = -N_1 \frac{d\varphi}{dt} \;\ldots\ldots\ldots(2)$$

Since ϕ is due to AC supply $\phi = \phi_m$ Sinwt

$$E_1 = -N_1 \frac{d}{dt}(\varphi_m \, \mathrm{Sinwt})$$

$$E_1 = -N_1 \, w\varphi_m \, \mathrm{Coswt}$$

$$E_1 = N_1 w\varphi_m \, \mathrm{Sin}(wt - \pi/2) \ldots\ldots\ldots(3)$$

So the induced emf lags flux by 90 degrees.

Maximum valve of emf

$$E_1 max = N_1 w\varphi_m \ldots\ldots\ldots(4)$$

But $w = 2\pi f$

$$E_1 max = 2\pi f N_1 \varphi_m \ldots\ldots\ldots(5)$$

Root mean square RMS value is

$$E_1 = \frac{E_{1max}}{\sqrt{2}} \ldots\ldots\ldots(6)$$

Putting the value of E_1max in equation (6) we get

$$E_1 = \sqrt{2}\pi f N_1 \varphi_m \ldots\ldots(7)$$

Putting the value of $\pi = 3.14$ in the equation (7) we will get the value of E_1 as

$$E_1 = 4.44 f N_1 \varphi_m \ldots\ldots\ldots(8)$$

Similarly

$$E_2 = \sqrt{2}\pi f N_2 \varphi_m$$

Or

$$E_2 = 4.44 f N_2 \varphi_m \dots \dots \dots (9)$$

Now, equating the equation (8) and (9) we get

$$\frac{E_2}{E_1} = \frac{4.44 f N_2 \varphi_m}{4.44 f N_1 \varphi_m}$$

Or

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

The above equation is called the **turn ratio** where K is known as the transformation ratio.

The equation (8) and (9) can also be written as shown below using the relation

($\phi m = B_m \times A_i$) where A_i is the iron area and B_m is the maximum value of flux density.

$$E_1 = 4.44 N_1 f B_m A_i \text{ Volts} \quad \text{and} \quad E_2 = 4.44 N_2 f B_m A_i \text{ Volts}$$

$$\frac{\text{R.M.S value}}{\text{Average value}} = \text{Form factor} = 1.11$$

For a sinusoidal wave

Here 1.11 is the form factor.

It's seen from *(i)* and *(ii)* that: **EMF Equation of the Transformer =**

$$\mathbf{E_1 / N_1 = E_2 / N_2 = 4.44 \times \mathit{f}\, \Phi_m.} \quad \dots\dots (i)$$

It means that **EMF / turn is the same in both the primary and secondary windings in the transformer** i.e. flux in Primary and Secondary Winding of the Transformer is same. Moreover, we already know that from the power equation of the transformer, i.e, in ideal

Transformer (there are no losses in transformer) on no-load,

$$V_1 = E_1$$

and

$$E_2 = V_2$$

Where,

- V_1 = supply voltage of primary winding
- E_2 = terminal voltage induced in the secondary winding of the transformer.

You may also read: Transformers Fire Protection System – Causes, Types & Requirements

VOLTAGE TRANSFORMATION RATIO (K)

As we have derived from the above EMF equation of the transformer *(iii);*

$$E_1 / N_1 = E_2 / N_2 = K$$

Where,

K = Constant

The constant **"K"** is known as **voltage transformation ratio**.

- If $N_2 > N_1$, i.e. $K > 1$, then the transformer is known as a step-up transformer.
- If $N_2 < N_1$, i.e. $K < 1$, then the transformer is called step-down transformer.

Where,

N_1 = Primary number of turns of the coil in a transformer.

N_2 = Secondary number of turns.

- You may also read: Current Transformers (CT) – Types, Characteristic & Applications

As, the losses in ideal transformer is assumed zero, this means input power is equal to the output power.

$$E_1 I_1 Cos\phi = E_2 I_2 Cos\phi$$

$$\frac{E_1}{E_2} = \frac{I_2}{I_1}$$

$$\frac{E_1}{E_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

Since E1 and E2 are directly proportional to number of turns in primary and secondary respectively, therefore

$E_1/E_2 = N_1/N_2$

Therefore, transformation ratio of transformer is given as below.

$$\frac{E_1}{E_2} = \frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

LOSSES IN TRANSFORMER

The transformer has no moving parts and hence the mechanical losses are absent in it. Hence, the losses in the transformer are considered as electrical energy losses. Two types of electrical losses are exist in a transformer which are core losses and copper losses.

Core or Iron Losses

These losses include both hysteresis and eddy current losses.

The magnetic flux set up in the transformer core is alternating type; thereby it undergoes a cycle of magnetization and demagnetization. During this, an appropriate power is required for continuous reversal of elementary magnets of the iron core. This is called as hysteresis effect and due to this considerable loss of energy takes place.

Hysteresis loss = Kh Bm1.67f v Watts

Where,

Kh = Hysteresis Constant

Bm = Maximum flux density

f= frequency

v = volume of the core

Since the transformer core is made up of ferromagnetic materials that are also good conductors. And hence, the magnetic flux linking with core induces emf in the core. Hence the core set up eddy currents in the core, thereby considerable eddy current losses occurs in the core.

Eddy Current losses = Ke Bm2f2t2 W/unit volume

Where,

Ke = Eddy current constant

t = thickness of the core

From the above two equations, it is to be observed that the supply voltage at a fixed frequency is constant and hence the flux in turn flux density in the core is almost constant. Therefore, both hysteresis and eddy current losses are constant during all loads. Hence the core losses are also called as constant losses.

By using the high grade core materials like silicon steel having very low hysteresis loop, hysteresis losses are minimized or reduced. On other hand, eddy current losses are minimized by using laminated core. These constant or core losses can be measured by conducting an open circuit on the transformer.

Copper Losses

These losses occur in the winding resistances of the transformer when it carries load current. The total copper loss in the transformer is obtained by adding both primary and secondary copper losses. These are found by conducting short circuit rest on the transformer.

Other losses in the transformer include dielectric losses and stray load losses. The stray losses are results from the eddy currents in the tank and winding conductors. Dielectric losses are occurs in the insulating materials like oil and solid insulations of the transformer.

TRANSFORMER EFFICIENCY

It is the ratio of useful power output to the power input of the transformer operating at a particular load and power factor.

Efficiency = Output/ Input

= Output / (Output + Total Losses) or

= (Input – Losses)/Input

= 1- (Losses/ Input)

Generally the efficiency of the transformer is in the range of 95 to 98%. From the above efficiency equation, it may be noted that the efficiency is depends on the watts, but not in volt-ampere rating. Hence, at any volt-ampere rating, the efficiency of the transformer depends on the power factor. The efficiency is maximum at unity power factor and is determined by calculating the total losses from OC and SC tests.

CONCEPT OF IDEAL TRANSFORMERS

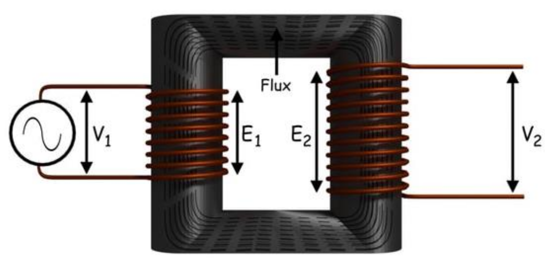
An **ideal transformer** is an imaginary transformer which has

- *no copper losses (no winding resistance)*

- *no iron loss in core*

- *no leakage flux*

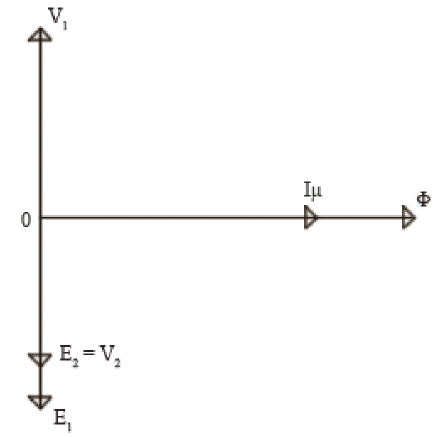
In other words, an ideal transformer gives output power exactly equal to the input power. The **efficiency of an idea transformer** is 100%. Actually, it is impossible to have such a transformer in practice, but **ideal transformer model** makes problems easier.



Characteristics Of Ideal Transformer

- Zero winding resistance: It is assumed that, resistance of primary as well as secondary winding of an ideal transformer is zero. That is, both the coils are purely inductive in nature.
- Infinite permeability of the core: Higher the permeability, lesser the mmf required for flux establishment. That means, if permeability is high, less magnetizing current is required to magnetize the transformer core.
- No leakage flux: Leakage flux is a part of magnetic flux which does not get linked with secondary winding. In an ideal transformer, it is assumed that entire amount of flux get linked with secondary winding (that is, no leakage flux).
- 100% efficiency: An ideal transformer does not have any losses like hysteresis loss, eddy

current loss etc. So, the output power of an ideal transformer is exactly equal to the input power. Hence, 100% efficiency.



- Now, if an alternating voltage V_1 is applied to the primary winding of an ideal transformer, counter emf E_1 will be induced in the primary winding. As windings are purely inductive, this induced emf E_1 will be exactly equal to the apply voltage but in 180 degree phase opposition. Current drawn from the source produces required magnetic flux. Due to primary winding being purely inductive, this current lags 90° behind induced emf E_1. This current is called magnetizing current of the transformer $I\mu$. This magnetizing current $I\mu$ produces alternating magnetic flux Φ. This flux Φ gets linked with the secondary winding and emf E_2 gets induced by mutual induction. (Read Faraday's law of electromagnetic induction.) This mutually induced emf E_2 is in phase with E_2. If closed circuit is provided at secondary winding, E_2 causes current I_2 to flow in the circuit.

- For an ideal transformer, $E_1I_1 = E_2I_2$.

DC MACHINES

INTRODUCTION TO DC MACHINES

- **DC Machines** are types of electrical machines that use dc current in the case of dc motors and generates dc voltages in case of dc generator.

- DC motor transforms electrical power into mechanical power and the generator converts mechanical power into electrical

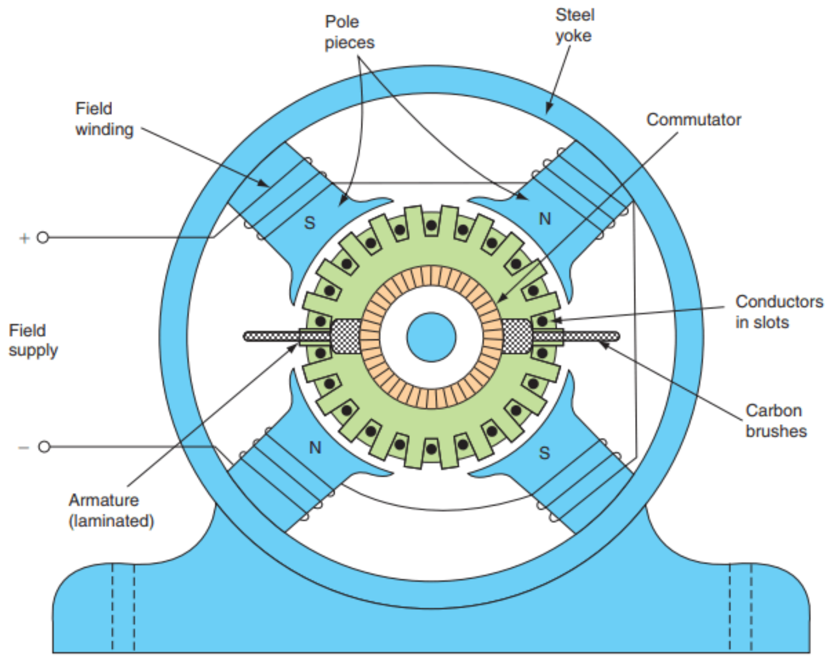
- As in power, generation system, and industries mostly ac machines like an induction motor, synchronous motor, generators are employed but the use of dc machines cannot be denied due to its constant speed providing the capability.

- The physical construction and designing of both dc motors and generators are alike to each other. The dc generator is used in some safe environment where is no need of special protection and circuitry for the generator.

- While the motor is employed in such an environment where it can be easily affected by environmental conditions like moisture, dust, so it needs a special structure that can provide resistant to dust, fire, and some other related effects.
- As we are familiar with the common use of dc battery that used only for some limited applications where less amount of energy is required but such applications where a large amount of dc power is needed dc machines is the best replacement of the battery.

DC MACHINES CONSTRUCTION

- There are numerous parts are exits in the designing and structure of dc machines like rotor, stator, windings and some others, all these part are described here with the detailed.



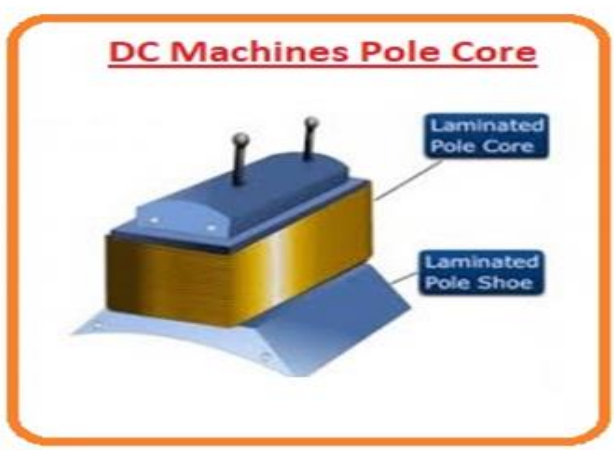
DC Machines Yoke

- The yoke of machines is also known as the frame, the main working of this part is to provide protection to the internal circuitry of a machine from the outer environment, temperature, moisture, and some other factors.
- This part of the machine is constructed with the cast steel and cast iron.

DC Machines Pole Core

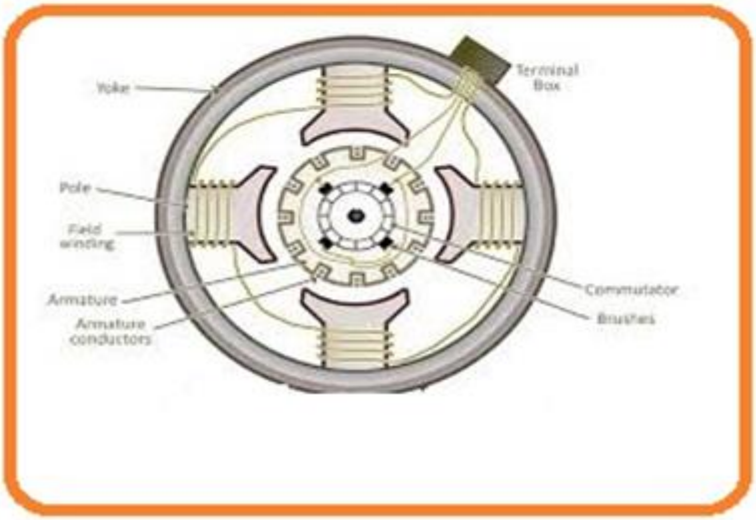
- At stator of the dc machines, the poles are of an electromagnet the windings on these poles are known as the field windings.
- The input provided at the stator connected with the field windings generate flux at the stator and make poles electromagnet.

These poles are constructed with cast steel, cast iron.



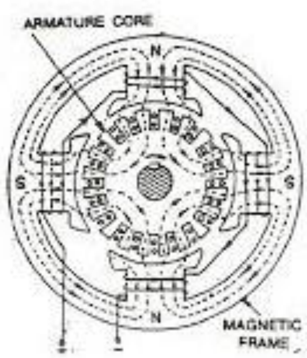
DC Machines Field Windings

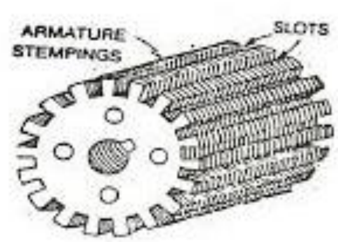
- These windings are wound at the sating part of machines on the poles at the stator. These windings are constructed with copper. The current provided at these windings generates flux and makes poles electromagnet.

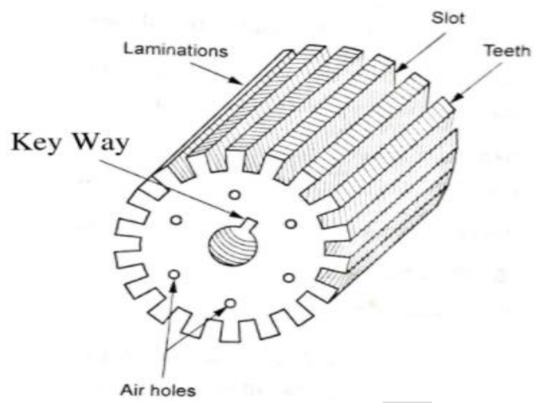


DC Machines Armature Core

- The core of armature consists of a large no of slots and armature windings are located in these slots.
- It has less reluctance path for the interaction of stator flux with the armature windings, this core is constructed with the less reluctance material like cast iron.
- And there are laminations of different substance is used to reduce the eddy current losses.







DC machines Armature Windings

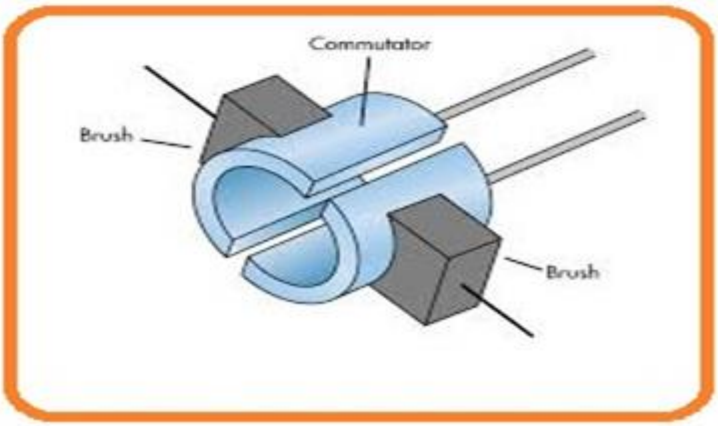
- The windings wound on the rotor if the dc machine is known as the armature windings. When the rotor rotates due to flux linking of stator the voltage induced in this part of machines.
- These windings are constructed with copper like the stator windings.

DC Machines Commutator

- The commutator is slip rings mounted at the shaft of the machines the main purpose of these commutators is to transmit current from the armature windings to the load.
- These commutators also convert ac power generated by the machine into the dc power, we will discuss this phenomenon how ac converts into dc by these commutators in coming tutorials.

Carbon Brushes

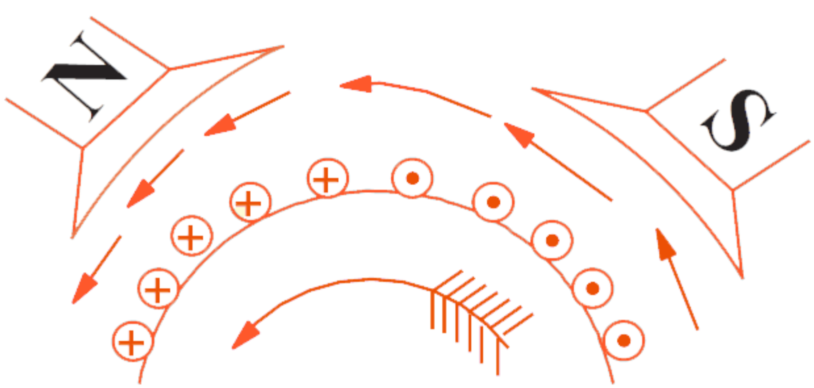
- These brushes are connected with the commutators and get current from the commutator and provides to the load.
- These are constructed with the carbon and their main function is to reduce the sparking at load and machine connection points.



Working of DC Motor

Consider a part of a **multipolar DC motor** as shown in the figure below. When the terminals of the motor are connected to an external source of DC supply:

- the **field magnets** are excited developing alternate North and South poles
- the **armature conductors** carry currents.

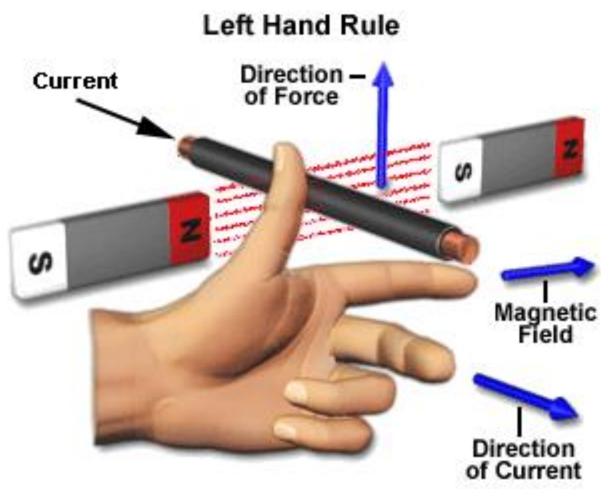


All conductors under North-pole carry currents in one direction while all the conductors under South-pole carry currents in the opposite direction.

The armature conductors under N-pole carry currents into the plane of the paper (denoted as ⊗ in the figure). And the conductors under S-pole carry currents out of the plane of the paper (denoted as ⊙ in the figure).

Since each armature conductor is carrying current and is placed in the magnetic field, a **mechanical force** acts on it.

On applying **Fleming's left-hand rule**, it is clear that force on each conductor is tending to rotate the armature in the anticlockwise direction. All these forces add together to produce a **driving torque** which sets the armature rotates.



When the conductor moves from one side of a brush to the other, the current in that conductor is reversed. At the same time, it comes under the influence of the next pole which is of opposite polarity. Consequently, the **direction of the force on the conductor remains the same**.

It should be noted that the **function of a commutator** in the motor is the same as in a generator. By reversing current in each conductor as it passes from one pole to another, it helps to develop a **continuous and unidirectional torque**.

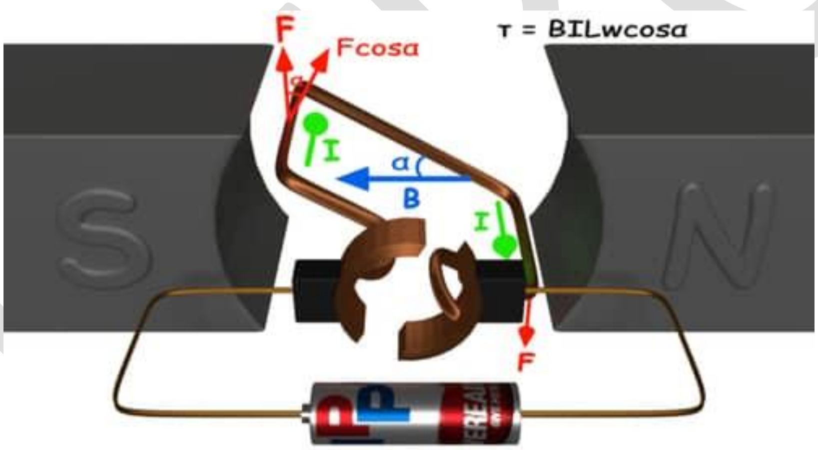
The torque produced is given by,

$$Torque = (force,\ tangential\ to\ the\ direction\ of\ armature\ rotation) \times (distance)$$

$$or,\ \tau = F\cos\alpha \times w$$

$$or,\ \tau = BILw\cos\alpha$$

Here α (alpha) is the angle between the plane of the armature turn and the plane of reference or the initial position of the armature which is here along the direction of magnetic field. The presence of the term cosα in the torque equation very well signifies that unlike force the torque at all position is not the same. It, in fact, varies with the variation of the angle α (alpha). To explain the variation of torque and the principle behind the rotation of the motor let us do a stepwise analysis.

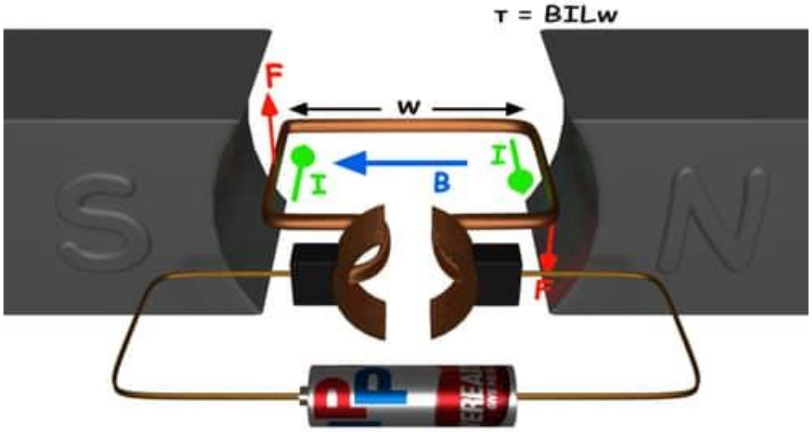


Step 1:

Initially considering the armature is in its starting point or reference position where the angle α =0.

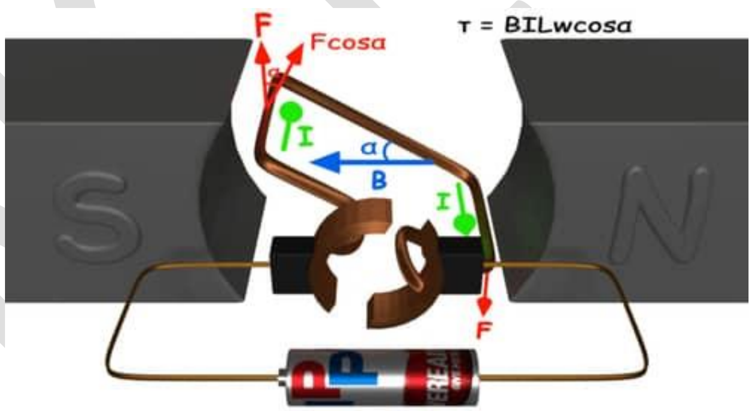
$$\therefore\ \tau = BILw \times \cos 0^\circ = BILw$$

Since, α = 0, the term cos α = 1, or the maximum value, hence torque at this position is maximum given by τ = BILw. This high starting torque helps in overcoming the initial inertia of rest of the armature and sets it into the rotation.



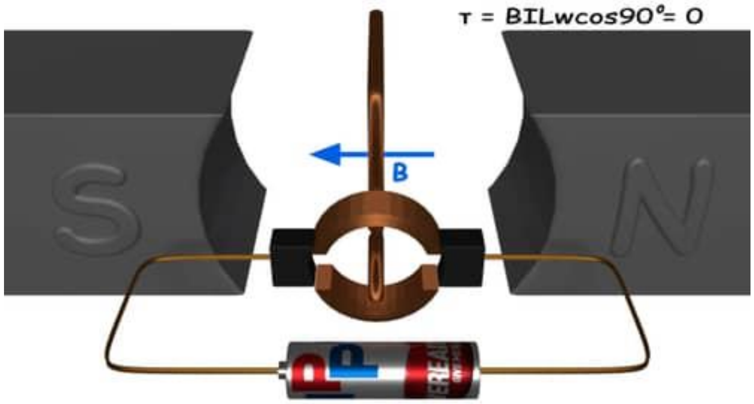
Step 2:

Once the armature sets in motion, the angle α between the actual position of the armature and its initial reference position goes on increasing in the path of its rotation until it becomes 90^o from its initial position. Consequently, the term cosα decreases and also the value of torque. The torque in this case is given by τ = BILwcosα which is less than BIL w when α is greater than 0^o.



Step 3:

In the path of the rotation of the armature a point is reached where the actual position of the rotor is exactly perpendicular to its initial position, i.e. α = 90^o, and as a result the term cosα = 0. The torque acting on the conductor at this position is given by, $\therefore \tau = BIL\omega \times \cos 90^o = 0$



i.e. virtually no rotating torque acts on the armature at this instance. But still the armature does not come to a standstill, this is because of the fact that the **operation of DC motor** has been engineered in such a way that the inertia of motion at this point is just enough to overcome this point of null torque. Once the rotor crosses over this position the angle between the actual position of the armature and the initial plane again decreases and torque starts acting on it again.

BACK EMF IN DC MOTOR

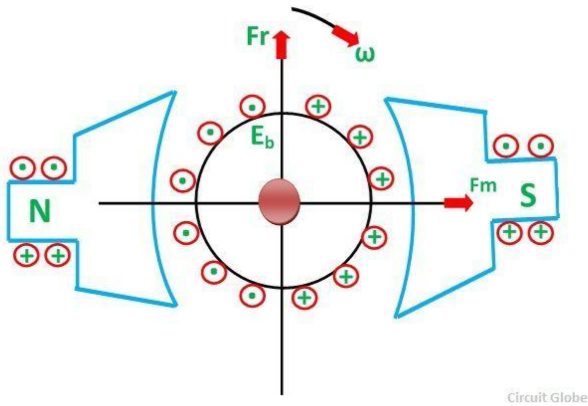
When the current-carrying conductor placed in a magnetic field, the torque induces on the conductor, the torque rotates the conductor which cuts the flux of the magnetic field. According to the Electromagnetic Induction Phenomenon "when the conductor cuts the magnetic field, EMF induces in the conductor"

The Fleming right-hand rule determines the direction of the induced EMF.

According to Fleming Right Hand Rule, if we hold our thumb, middle finger and index finger of the right hand by an angle of 90°, then the index finger represents the direction of the magnetic field. The thumb shows the direction of motion of the conductor and the middle finger represents the emf induces on the conductor.

On applying the right-hand rule in the figure shown below, it is seen that the direction of the induced emf is opposite to the applied voltage. Thereby the emf is known as the *counter emf or back emf*.

The back emf is developed in series with the applied voltage, but opposite in direction, i.e., the back emf opposes the current which causes it.

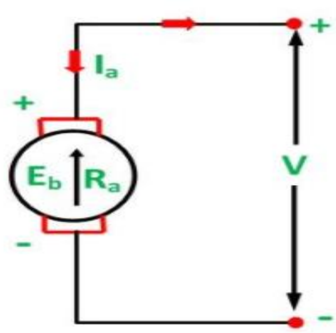


The magnitude of the back emf is given by the same expression shown below:

$$E_b = \frac{NP\varphi Z}{60\ A}$$

Where E_b is the induced emf of the motor known as Back EMF, A is the number of parallel paths through the armature between the brushes of opposite polarity. P is the number of poles, N is the speed, Z is the total number of conductors in the armature and ϕ is the useful flux per pole.

A simple conventional circuit diagram of the machine working as a motor is shown in the diagram below:



In this case, the magnitude of the back emf is always less than the applied voltage. The difference between the two is nearly equal when the motor runs under normal conditions.

The current induces on the motor because of the main supply. The relation between the main supply, back emf and armature current is given as $E_b = V – I_aR_a$.

THREE PHASE INDUCTION MOTORS

INTRODUCTION

The motor is used to convert an electrical form of energy into mechanical form. According to the type of supply, motors are classified as AC motors and DC motors. In today post, we will discuss the different types of three phase induction motors with working and applications.

The induction motor especially three phase induction motors are widely used AC motor to produce mechanical power in industrial applications. Almost 80% of the motor is a three-phase induction motor among all motors used in industries. Therefore, the induction motor is the most important motor among all other types of motor**.**

What is a 3-Phase Induction Motor?

A three phase induction motor is a type of AC induction motors which operates on three phase supply as compared to the single phase induction motor where single phase supply is needed to operate it. The three phase supply current produces an electromagnetic field in the stator winding which leads to generate the torque in the rotor winding of three phase induction motor having magnetic field.

CONSTRUCTION OF THREE PHASE INDUCTION MOTOR

Like any electric motor, a 3-phase induction motor has a stator and a rotor. The stator carries a 3-phase winding (called stator winding) while the rotor carries a short-circuited winding (called rotor winding).

Only the stator winding is fed from the 3-phase supply. The rotor winding derives its voltage and power from the externally energized stator winding through **electromagnetic induction** and hence the name.

A 3-phase induction motor has two main parts

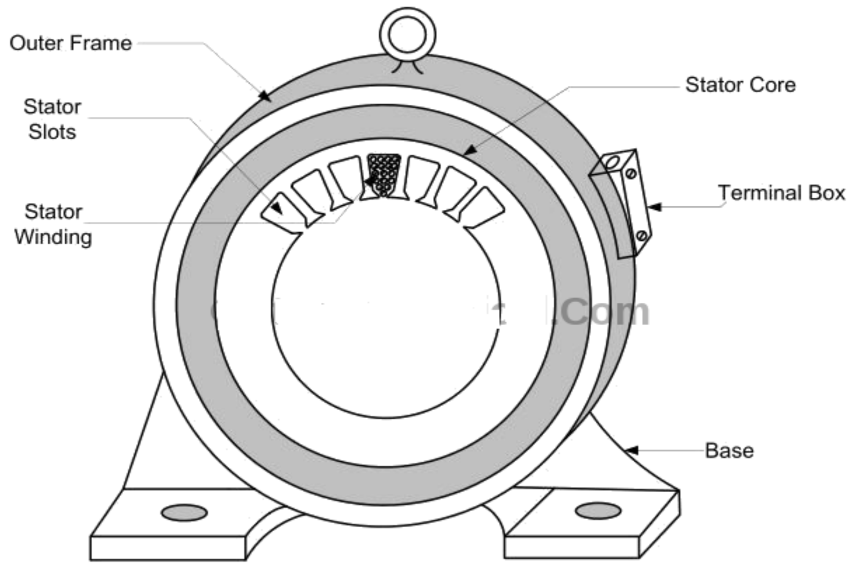
1. **Stator**
2. **Rotor**

The rotor is separated from the stator by a small **air-gap** which ranges from 0.4 mm to 4 mm, depending on the power of the motor.

1. STATOR OF 3-PHASE INDUCTION MOTOR

The stator consists of a steel frame that encloses a hollow, cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current losses.

A number of evenly spaced slots are provided on the inner periphery of the laminations. The insulated conductors are connected to form a balanced 3-phase star or delta connected circuit.



Outer frame and stator of three-phase induction motor

The 3-phase stator winding is wound for a definite number of poles as per the requirement of speed. Greater the number of poles, lesser is the speed of the motor and vice-versa.

When 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude is produced. This rotating field induces currents in the rotor by electromagnetic induction.

As the name suggests, the stator is a stationary part of the motor. The stator of the induction motor consists of three main parts;

- **Stator Frame**
- **Stator Core**
- **Stator Winding**

Stator Frame

The stator frame is the outer part of the motor. The function of the stator frame is to provide support to the stator core and stator winding.

It provides mechanical strength to the inner parts of the motor. The frame has fins on the outer surface for heat dissipation and cooling of the motor.

The frame is casted for small machines and it is fabricated for a large machine. According to the applications, the frame is made up of die-cast or fabricated steel, aluminum/ aluminum alloys, or stainless steel.

Stator Core

The function of the stator core is to carry the alternating magnetic flux which produces hysteresis and eddy current loss. To minimize these losses, the core is laminated by high-grade steel stampings thickness of 0.3 to 0.6 mm.

These stampings are insulated from each other by varnish. All stampings stamp together in the shape of the stator core and fixed it with the stator frame.

An inner layer of the stator core has a number of slots.

Stator Winding

The stator winding is placed inside the stator slots available inside the stator core. Three-phase winding is placed as a stator winding. And three-phase supply is given to the stator winding.

The number of poles of a motor depends on the internal connection of the stator winding and it will decide the speed of the motor. If the number of poles is greater, the speed will less and if the number of poles is lesser than the speed will high. The poles are always in pairs. Therefore, the total number of poles always an even number. The relation between synchronous speed and number poles is as shown in the below equation,

$$N_S = 120f / P$$

Where;

- f = Supply Frequency
- P = Total Number of Poles
- N_s = Synchronous Speed

As the end of winding connected to the terminal box. Hence, there are six terminals (two of each phase) in the terminal box.

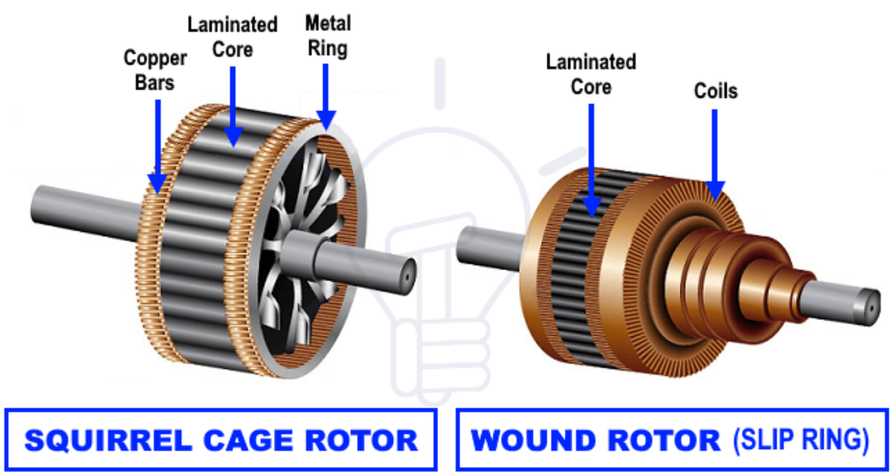
According to the application and type of starting methods of motors, the stator winding is connected in star or delta and it is done by the connection of terminals in the terminal box.

2. ROTOR OF 3-PHASE INDUCTION MOTOR

The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery. The winding placed in these slots (called rotor winding) may be one of the following two types:

1. Squirrel Cage Type
2. Wound Rotor Type

The construction of the stator is same in both types of induction motors. We will discuss the types of rotors used in 3-phase induction motors in the following section of types of three phase induction motors.



TYPES OF THREE PHASE INDUCTION MOTORS

Three phase motors are classified mainly in two categories based on the rotor winding (Armature coil winding) i.e. squirrel cage and slip ring (wound rotor motor).

- **Squirrel Cage Induction Motor**
- **Slip-ring or Wound Rotor Induction Motor**

SQUIRREL CAGE INDUCTION MOTOR

The shape of this rotor is resembling the shape of the cage of a squirrel. Therefore, this motor is known as a squirrel cage induction motor.

The construction of this type of rotor is very simple and rugged. So, almost 80% of the induction motor is a squirrel cage induction motor.

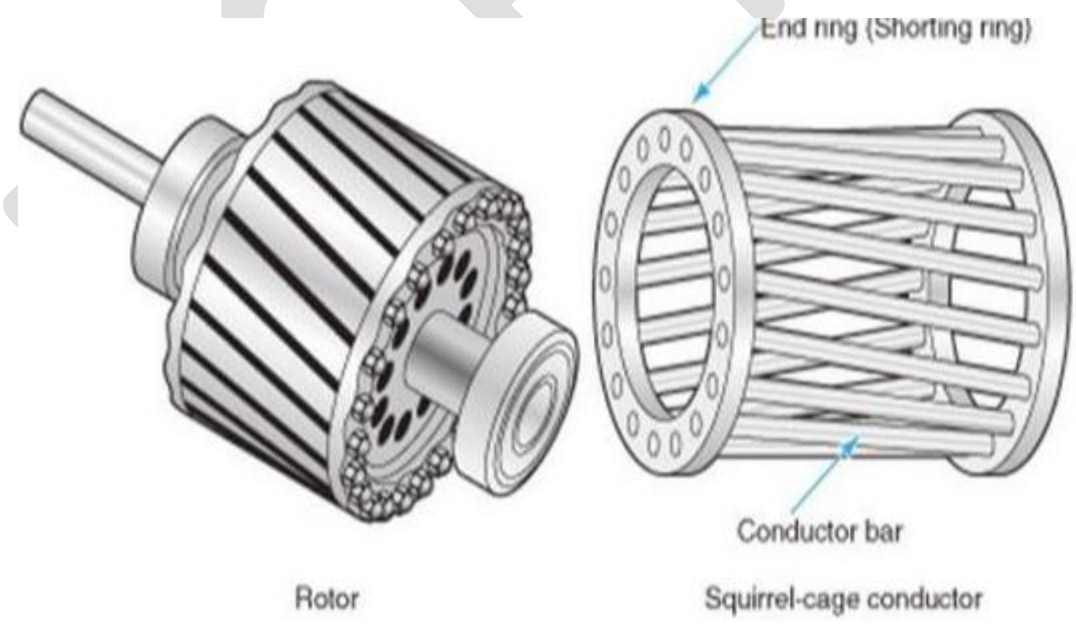
The rotor consists of a cylindrical laminated core and has slots on the outer periphery. The slots are not parallel but it is skewed at some angle. It helps to prevent magnetic locking between the stator and rotor teeth. It results in smooth operation and reduces the humming noise. It increases the length of the rotor conductor due to this the rotor resistance is increased.

The squirrel cage rotor consists of rotor bars instead of the rotor winding. The rotor bars are made up of aluminum, brass, or copper.

Rotor bars are permanently shorted by end rings. So, it makes a complete close path in the rotor circuit. The rotor bars are welded or braced with the end rings to provide mechanical support.

The rotor bars are short-circuited. Therefore, it is not possible to add external resistance to the rotor circuit.

In this type of rotor, the slip rings and brushes are not used. Hence, the construction of this type of motor is simpler and more robust.



SLIP-RING OR WOUND ROTOR INDUCTION MOTOR

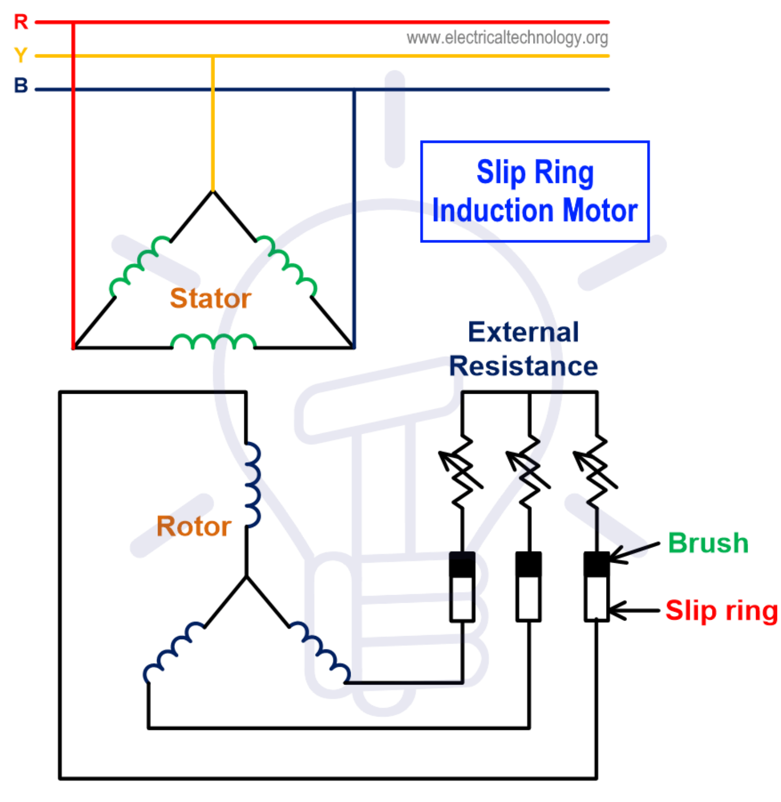
Slip-ring induction motors are also known as wound rotor motor. The rotor consists of a laminated cylindrical core with slots on the outer periphery. The rotor winding is placed inside the slots.

In this type of rotor, the rotor winding is wounded in such a way that, the number of poles of rotor winding is the same as the number of poles of the stator winding. The rotor winding can be connected as a star or delta.

End terminals of rotor windings are connected to the slip-rings. So, this motor is known as a slip-ring induction motor.

The external resistance can easily connect with the rotor circuit through the slip-ring and brushes. And it is very useful for controlling the speed of the motor and improving the starting torque of the three-phase induction motor.

An electrical diagram of slip-ring three-phase induction motor with external resistance is shown in the below figure.



The external resistance is used only for the starting purpose. If it is remains connected during the running condition, it will increase the rotor copper loss.

High rotor resistance is good for the starting condition. So, the external resistance is connected with the rotor circuit during the starting condition.

When motor running near the speed of the actual speed, the slip-rings are short-circuited by the metal collar. By this arrangement, the brushes and external resistance is removed from the rotor circuit.

This reduces the rotor copper loss as well as friction in brushes. The rotor construction is a little bit complicated compared to the squirrel cage motor due to the presence of brushes and slip-rings.

The maintenance of this motor is more. So, this motor only used when variable speed control and high starting torque are needed. Otherwise, the squirrel cage induction motor is more preferred over slip-ring induction motor.

Advantages & Disadvantages of Induction Motors

Advantages

The advantages of induction motor are listed as below,

- The construction of a motor is very simple and robust.
- The working of an induction motor is very simple.
- It can operate in any environmental condition.
- The efficiency of the motor is very high.
- The maintenance of an induction motor is less compared to other motors.
- It is a single excited motor. Hence, it needs only one supply of source. It does not require external DC supply for excitation like a synchronous motor.
- The induction motor is a self-starting motor. So, it does not require any extra auxiliaries for the starting purpose for normal operation.
- The cost of this motor is very less compared to other motors.
- The life span of this motor is very high.
- Armature reaction is less.

Disadvantages

The disadvantages of the motor are listed as below;

- During light load condition, the power factor is very less. And it draws more current. So, the copper loss is more which reduce the efficiency during light load condition.
- The starting torque of this motor (squirrel cage induction motor) is not less.
- The induction motor is a constant speed motor. For the application where variable speed requires, this motor is not used.
- Speed control of this motor is difficult.
- The induction motor has a high starting inrush current. This causes a reduction in voltage at the time of starting.

Application of 3-Phase Induction Motors

The induction motor is mostly used in industrial applications. The **squirrel cage induction motors** are used in residential as well as industrial applications especially where the speed control of motors is not needed such as:

- Pumps and submersible
- Pressing machine
- Lathe machine
- Grinding machine
- Conveyor
- Flour mills
- Compressor
- And other low mechanical power applications

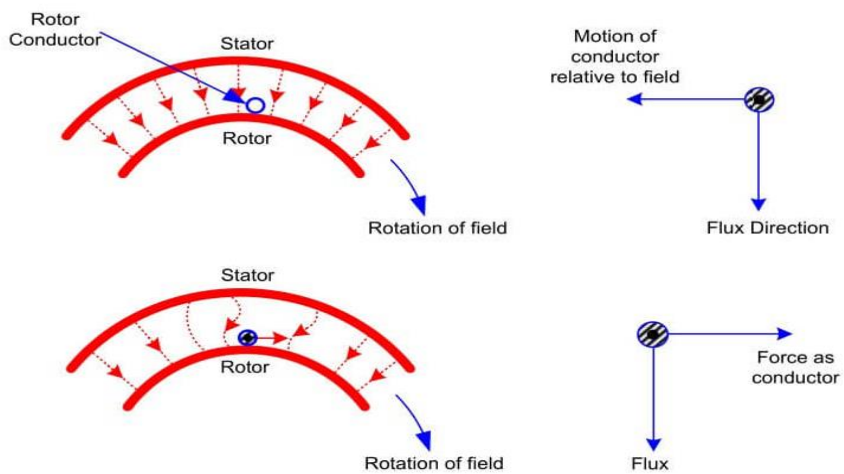
The **slip ring motors** are used in heavy load applications where the high initial torque is needed such as:

- Steel mills
- Lift
- Crane Machine

- Hoist
- Line shafts
- and other heavy mechanical workshops etc

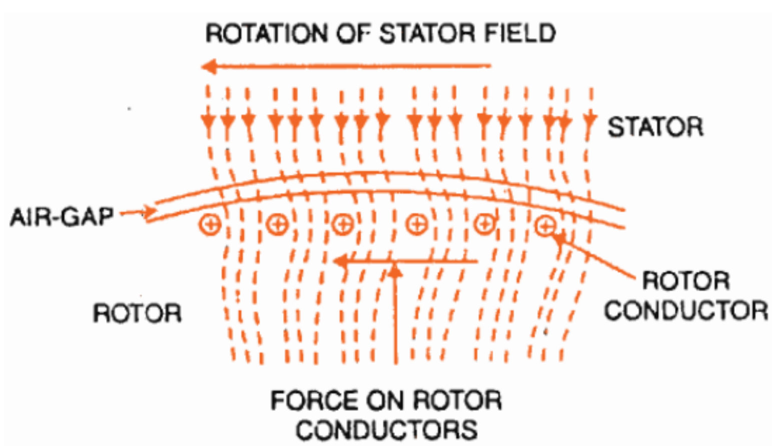
WORKING PRINCIPLE THREE PHASE INDUCTION MOTOR

For explaining the principle of operation of a three-phase induction motor, consider a portion of the three-phase induction motor as shown in the figure.



The working of the three-phase induction motor is based on the principle of electromagnetic induction.

When three-phase stator winding of an induction motor is energized from a 3 phase supply, a rotating magnetic field is set up which rotates around the stator at synchronous speed (N_s).



Synchronous Speed,

$N_s = 120 f/P$

Where,

f = frequency

P = Number of Poles

(For more details about rotating magnetic field, read Production of rotating magnetic field).

This rotating field passes through the air gap and cuts the rotor conductors, which are stationary.

An EMF gets induced in every rotor conductor due to the relative speed between the rotating magnetic flux and the stationary rotor. Since the rotor circuit is short-circuited, currents start flowing in the rotor conductors.

The current-carrying rotor conductors are placed in the magnetic field produced by the stator. Consequently, a **mechanical force** acts on the rotor conductors. The sum of the mechanical forces on all the rotor conductors produces a **torque** which tends to move the rotor in the same direction as the rotating field.

The fact that the rotor is urged to follow the stator field (i.e., rotor moves in the direction of stator field) can be explained by **Lenz's law**.

According to Lenz's law, the direction of rotor currents will be such that they tend to oppose the cause of producing them.

Now, the cause producing the rotor currents is the relative speed between the rotating field and the stationary rotor conductors.

Hence to reduce this relative speed, the rotor starts running in the same direction as that of the stator field and tries to catch it. This is how a three-phase induction motor starts running.

SLIP IN INDUCTION MOTOR

We have seen above that the rotor rapidly accelerates in the direction of the rotating magnetic field.

In practice, the rotor can never reach the speed of stator flux. If it did, there would be no relative speed between the stator field and rotor conductors, no induced rotor currents and, therefore, no torque to drive the rotor.

The friction and windage would immediately cause the rotor to slow down. Hence, the rotor speed (N) is always less than the stator field speed (N_s). This difference in speed depends upon load on the motor.

The difference between the synchronous speed N_s of the rotating stator field and the actual rotor speed N is called **slip in a three-phase induction motor**.

Slip is usually expressed as a percentage of synchronous speed i.e.,

Slip, $s = (N_s - N)/N_s \times 100$ %

The quantity N s – N is sometimes called **slip speed**.

When the rotor is stationary (i.e., N = 0), slip, s = 1 or 100 %.

Why the slip is never zero in an induction motor?

When the actual speed of the rotor is equal to the synchronous speed, the slip is zero. For the induction motor, this condition will never happen.

Because when the slip is zero, both speeds are equal and there is no relative motion. Therefore, no EMF induced in the rotor circuit and rotor current is zero. Hence, the motor cannot run.

In an induction motor, the change in slip from no-load to full-load is hardly **0.1% to 3%** so that it is essentially a **constant-speed motor**.

SINGLE PHASE INDUCTION MOTORS

The single-phase motors are more preferred over a three-phase induction motor for domestic, commercial applications. Because form utility, only single-phase supply is available. So, in this type of application, the three-phase induction motor cannot be used.

CONSTRUCTION OF SINGLE-PHASE INDUCTION MOTOR

A single phase induction motor is similar to the three phase squirrel cage induction motor except there is single phase two windings (instead of one three phase winding in 3-phase motors) mounted on the stator and the cage winding rotor is placed inside the stator which freely rotates with the help of mounted bearings on the motor shaft.

The construction of a single-phase induction motor is similar to the construction of a three-phase induction motor.

Similar to a three-phase induction motor, single-phase induction motor also has two main parts;

- Stator
- Rotor

Stator

In stator, the only difference is in the stator winding. The stator winding is single-phase winding instead of three-phase winding. The stator core is the same as the core of the three-phase induction motor.

In a single-phase induction motor, there are two winding are used in stator except in shaded-pole induction motor. Out of these two windings, one winding is the main winding and the second is auxiliary winding.

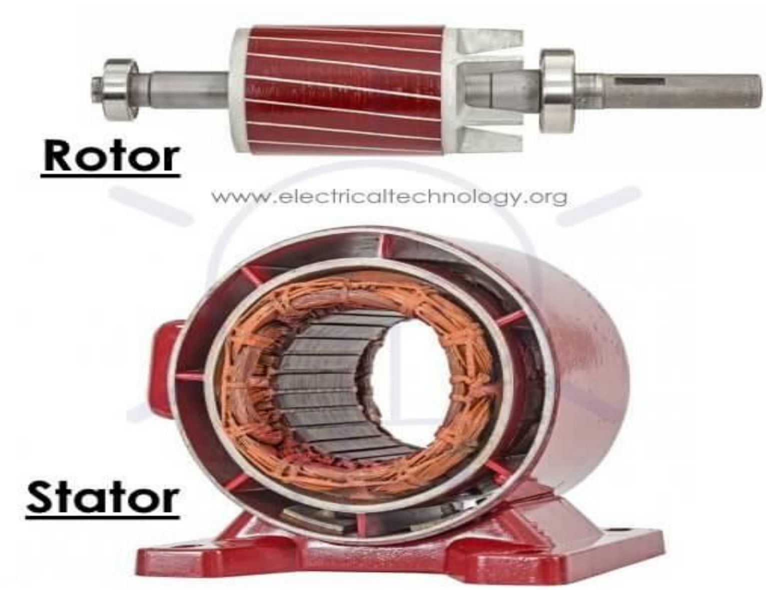
The stator core is laminated to reduce the eddy current loss. The single-phase supply is given to the stator winding (main winding)

Rotor

Rotor of single-phase induction motor is the same as a rotor of squirrel cage induction motor. Instead of rotor winding, rotor bars are used and it is short-circuited at the end by end-rings. Hence, it makes a complete path in the rotor circuit. The rotor bars are braced to the end-rings to increase the mechanical strength of the motor.

The rotor slots are skewed at some angle to avoid magnetic coupling. And it also used to make a motor run smooth and quiet.

The following fig shows the stator and rotor of a 1-phase induction motor.



WORKING OF SINGLE-PHASE INDUCTION MOTOR

Single-phase AC supply is given to the stator winding (main winding). The alternating current flowing through the stator winding produces magnetic flux. This flux is known as the main flux.

Now we assume that the rotor is rotating and it is placed in a magnetic field produced by the stator winding. According to Faraday's law, the current start flowing in the rotor circuit it is a close path. This current is known as rotor current.

Due to the rotor current, the flux produced around the rotor winding. This flux is known as rotor flux.

There are two fluxes; **main flux which is produced by stator** and second is the **rotor flux which is produced by the rotor**.

Interaction between main flux and rotor flux, the torque produced in the rotor and it starts rotating.

The stator field is alternating in nature. The speed of the stator field is the same as synchronous speed. The synchronous speed of the motor depends on the number of pole and supply frequency.

It can represent by two revolving fields. These fields are equal in magnitude and rotating in the opposite direction.

Let say Φ_m is a maximum field induced in the main winding. So, this field is divided into two equal parts and that is $\Phi_m/2$ and $\Phi_m/2$.

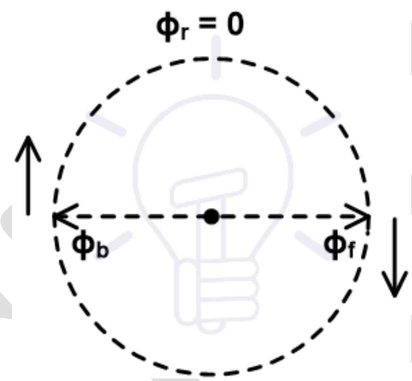
Out of these two fields, one field Φ_f is rotating in an anticlockwise direction and the second field Φ_b is rotating in a clockwise direction. Therefore, the resultant field is zero.

$$\Phi_r = \Phi_f - \Phi_b$$

$$\Phi_r = \frac{\Phi_m}{2} - \frac{\Phi_m}{2}$$

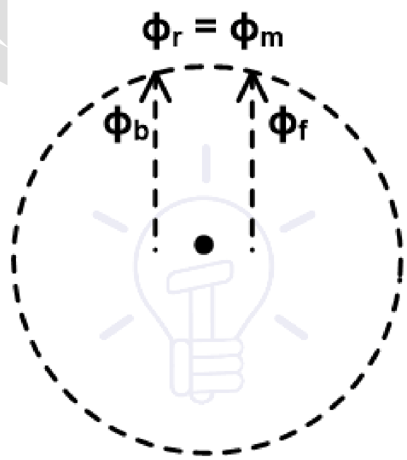
$$\mathbf{\Phi_r = 0}$$

Now consider the resultant field at different instants.



When a motor starts, two fields are induced as shown in the above figure. These two fields are the same magnitude and opposite direction. So, resultant flux is zero.

In this condition, the stator field cannot cut by rotor field and resultant torque is zero. So, the rotor cannot rotate but it produces humming.



Now consider after the rotation of 90˚, both filed are rotated and pointing in the same direction.

Therefore, the resultant flux is a summation of both fields.

$$\Phi_r = \Phi_f + \Phi_b$$

$$\Phi_r = \frac{\Phi_m}{2} + \frac{\Phi_m}{2}$$

$$\mathbf{\Phi_r = 0}$$

In this condition, the resultant filed is equal to the maximum field induced by the stator. Now, both fields rotate separately and it is alternative in nature.

So, both fields cut by the rotor circuit and EMF induced in the rotor conductor. Due to this EMF, the current starts flowing in the rotor circuit and it induces a rotor flux.

Due to the interaction between stator flux and rotor flux motor continues to rotate. T**his theory is known as Double Revolving Theory** or **double field revolving theory**.

Now, from the above explanation, we can conclude that the single-phase induction motor is not self-starting.

To make this motor self-starting motor, we need stator flux rotating in nature instead of alternating nature. This can be done by various methods.

Single-phase induction motor can be classified according to starting methods.

Types of Single-phase Induction Motors

The single-phase induction motors are classified as;

- Split Phase Induction Motor
- Shaded Pole Induction Motor
- Capacitor Start Induction Motor
- Capacitor Start Capacitor Run Induction Motor
- Permanent Capacitor Induction Motor

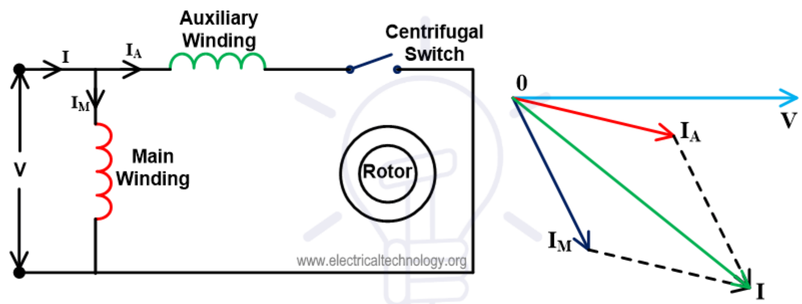
SPLIT PHASE INDUCTION MOTOR

In this type of motor, an extra winding is wounded on the same core of the stator. So, there are two windings in the stator.

One winding is known as the main winding or running winding and second winding is known as starting winding or auxiliary winding. A centrifugal switch is connected in series with the auxiliary winding.

The auxiliary winding is highly resistive winding and the main winding is highly inductive winding. The auxiliary winding has few turns with a small diameter.

The aim of auxiliary winding is to create a phase difference between both fluxes produced by the main winding and rotor winding.



Split Phase Induction Motor

The connection diagram is as shown in the above figure. The current flowing through the main winding is I_M and current flowing through the auxiliary winding is I_A. Both windings are parallel and supplied by voltage V.

The auxiliary winding is highly resistive in nature. So, the current I_A is almost in phase with supply voltage V.

The main winding is highly inductive in nature. So, the current I_M lags behind the supply voltage with a large angle.

The total stator flux is induced by the resultant current of these two winding. As shown in the phasor diagram, the resultant current is represented as (I). It will create a phase difference between fluxes and resultant flux produces a rotating magnetic field. And the motor starts rotating.

Auxiliary winding only uses to start the motor. This winding is not useful in running condition. When the motor reaches 75 to 80 % of synchronous speed, the centrifugal switch opens. So, the auxiliary winding is out from the circuit. And motor runs on only main winding.

The phase difference creates by this method is very small. Hence, the starting torque of this motor is poor. So, this motor is used in low starting torque applications like a fan, blower, grinder, pumps, etc.

SHADED POLE INDUCTION MOTOR

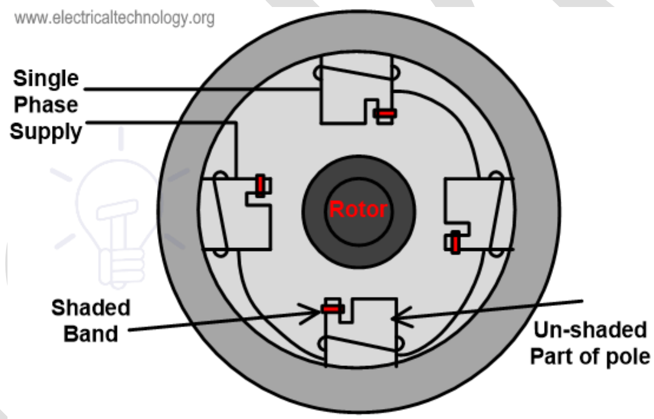
As compared to other types of single-phase induction motor, this motor has a different construction and working principle. This type of motor does not require auxiliary winding.

This motor has stator salient pole or projecting pole and the rotor is the same as squirrel cage induction motor. The stator poles are constructed specially to create a rotating magnetic field.

A pole of this motor is divided into two parts; shaded part and un-shaded part. It can be created by cutting pole into unequal distances.

A copper ring is placed in the small part of the pole. This ring is a highly inductive ring and it is known as a shaded ring or shaded band. The part at which shaded ring is paced is known as shaded part of the pole and the remaining part is an unshaded part.

The construction of this motor is as shown in the below figure.



Shaded Pole Induction Motor

When an alternating supply passing through the stator winding, an alternating flux induced in the stator coil. Due to this flux, some amount of flux will link with shaded ring and current will flow through a shaded ring.

According to Len'z law, the current passing through coil is opposite in nature, and flux produced due to this coil will oppose the main flux.

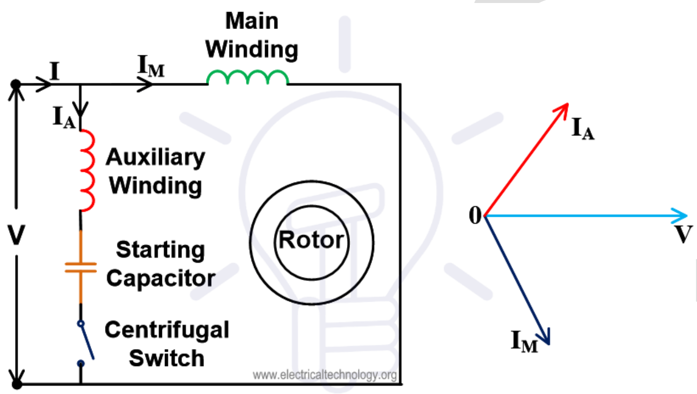
The shaded ring is a highly inductive coil. So, it will oppose the main flux when both fluxes are in the same direction and it will increase the main flux when both fluxes are in the opposite direction.

So, it will create a phase difference between the main flux (stator flux) and rotor flux. By this method, a phase difference is very less. Hence, the starting torque is very less. It is used in applications like toy motor, fan, blower, record player, etc

CAPACITOR START INDUCTION MOTOR

This type of motor is an advanced version of the Split phase induction motor. The disadvantage of split-phase induction is low torque production. Because in this motor, the phase difference created is very less.

This disadvantage compensates in this motor with the help of a capacitor connected in series with auxiliary winding. The circuit diagram of this motor is as shown in the below figure.



Capacitor Start Induction Motor

The capacitor used in this motor is a dry-type capacitor. This is designed to use with alternating current. But this capacitor is not used for continuous operation.

In this method also, a centrifugal switch is used which disconnects the capacitor and auxiliary winding when the motor runs 75-80% of synchronous speed.

The current through auxiliary will lead the supply voltage by some angle. This angle is more than the angle increased in a split-phase induction motor.

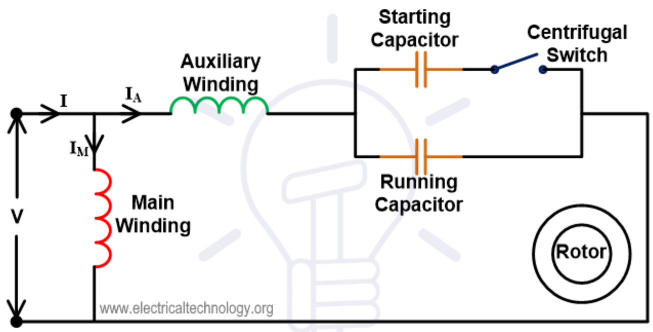
So, the starting torque of this motor is very high compared to the split-phase induction motor. The starting torque of this motor is 300% more than the full load torque.

Due to high starting torque, this motor is used in the applications where high starting torque is required like, a Lath machine, compressor, drilling machines, etc.

CAPACITOR START CAPACITOR RUN INDUCTION MOTOR

In this type of motor, two capacitors are connected in parallel with series in auxiliary winding. Out of these two capacitors, one capacitor is used only for starting (starting capacitor) and another capacitor is connected permanently with the motor (running capacitor).

The circuit diagram of this figure is as shown in the below figure.



Capacitor Start Capacitor Run Induction Motor

The starting capacitor has high capacitance value and a running capacitor has low capacitance value. The starting capacitor is connected in series with a centrifugal switch that will open when the speed of the motor is 70% of synchronous speed.

During running conditions, both running winding and auxiliary winding connected with motor. The starting torque and efficiency of this motor are very high.

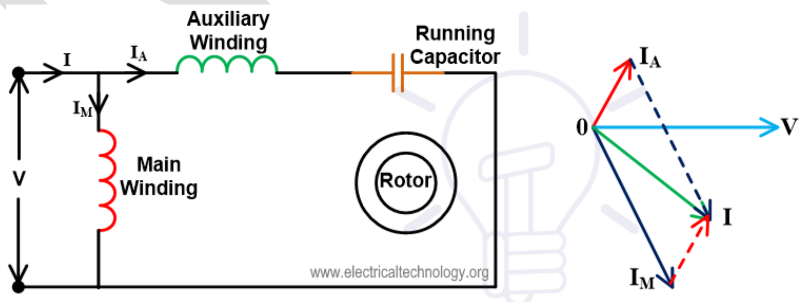
Therefore, this can be used in the application where high starting torque is required like a refrigerator, air conditioner, ceiling fan, compressor, etc.

PERMANENT CAPACITOR INDUCTION MOTOR

The low-value capacitor is connected constantly with the auxiliary winding. Here, the capacitor has low capacitance.

The capacitor is used to increase the starting torque but it is low compared to the capacitor start induction motor.

The circuit diagram and phasor diagram of this motor is as shown in the below figure.



Permanent Capacitor Induction Motor

The power factor and efficiency of this motor are very high and also it has a high starting torque that is 80% of full load torque.

This type of motor is used in the application like an exhaust fan, blower, heater, etc.

Applications of Single Phase Induction Motors

Single phase motors are not self starting and less efficient than three phase induction motor and available in 0.5HP to 15HP and still they are widely used for multiple purposes such as:

- Clocks
- Refrigerators, freezers and heaters
- Fans, table fans, ceiling fan, exhaust fans, air coolers and water coolers.
- Blowers
- Washing machines
- machine tools
- Dryers
- Type writers, photostats and printers
- Water pumps and submersible
- Computers
- Grinders
- Drilling machines
- Other Home instrument, equipment and devices etc.

UNIVERSAL MOTORS

The type of motor which operates on both DC and single phase AC supply is called **Universal Motor**. The universal motor is also called an **ac series motor**. The universal motor works at approximately the same speed and output on either DC or AC single-phase supply.

The universal motor is a series-wound motor that means field winding and armature windings are connected in series. It has high starting torque and variable speed characteristics. It runs at dangerously high speed when run at no load.

Universal motors are designed for commercial frequencies from 50Hz or 60Hz to DC zero frequency and for voltage rating 250V to 1.5V.

Universal motors are generally used in Electric hand drills, vacuum cleaners, electric shaver, sewing machines, and in many more applications.

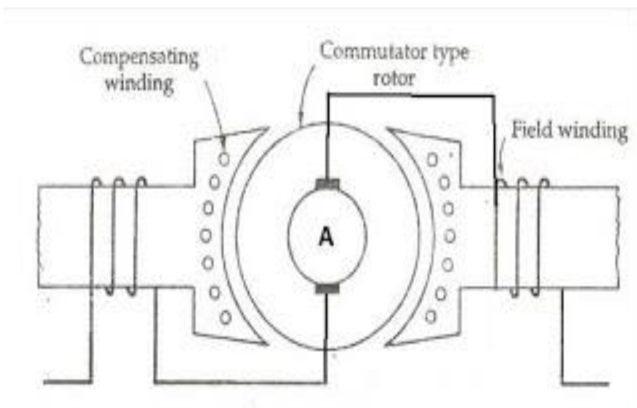
This motor is a commutator type motor.

If an ac series motor is connected to an AC supply it will rotate and exert one-directional torque because the current flowing in both field and armature is the same and reverse at the same time.

The direction of torque developed in DC series motor is determined by both field polarity and the direction of current flowing through armature winding.

Construction Of Universal Motor

The construction of a universal motor is identical to the construction of a DC series motor. It is a series-wound motor that means field and armature windings are connected in series. the universal motor diagram is shown below



Universal-Motor-Diagram

Types of Universal Motor

Generally constructed in two types

- Non compensated with concentrated pole type

- Compensated with distributed field type

Non compensated with concentrated pole types

The non compensated type universal motor has 2 salient poles like DC series motor except the laminated core. The laminated stator is constructed to reduced eddy current losses because the flux is alternating when it operated on AC supply.

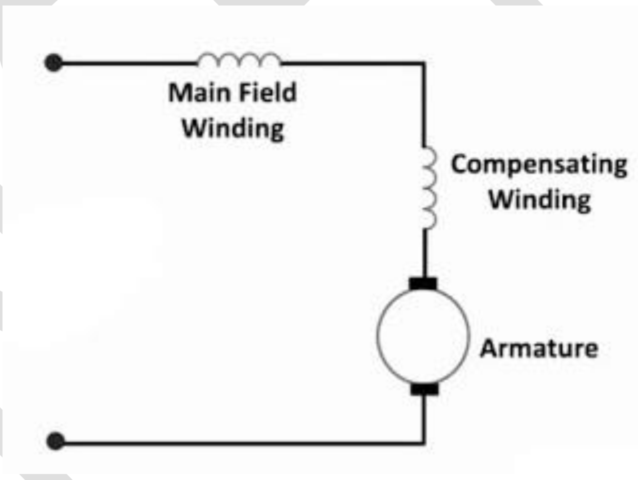
The armature is wound type same as small dc motor, it has laminated core having straight or skewed slots and commutator to which armature winding leads are connected.

Compensated with Distributed field type

It has a stator same as the split-phase motor and wound type armature similar to that small dc motor.

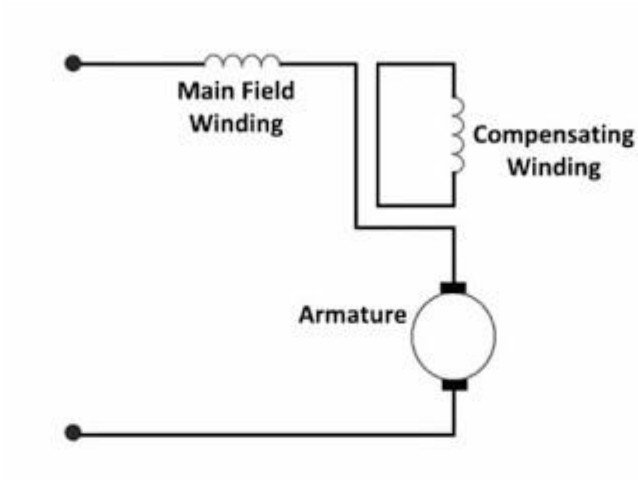
In compensated type motor, compensating winding is used to reduced reactance voltage drop in armature when it operated on AC supply. This voltage is caused by the transformer action due to alternating flux.

If compensated winding connected in series with armature and field winding in such a case motor is called a **conductively compensated motor.** the connection diagram is shown below.



conductively compensated motor

And in other cases, if compensating winding short-circuited on itself in such a case motor is called **inductively compensated** and received excitation voltage by transformer action since it is inductively coupled. the circuit diagram is shown in the below image.



Inductively compensated universal-motor

Working Principle of Universal Motor(AC Series Motor)

Let,

DC series motor connected to single-phase ac supply and the same current flowing through the field and armature windings., hence the ac reversal from positive to negative cycle or from negative cycle to positive will simultaneously affect both field flux polarity and the current direction through armature winding. This shows that the direction of torque developed will remain positive and rotor rotation will continue in the same direction. Thus, independent of supply fed. universal motors working principle is the same as the DC series motor works.

The nature of torque developed will be pulsating and frequency will be twice the supply frequency. thus universal motor(ac series motor) can run on both DC and single phase AC supply.

AC series motor specially design to run on DC supply suffers following drawbacks when it operated on a single phase AC source.

Its efficiency is low due to hysteresis and eddy current losses.

- Its Power factor is low due to the large reactance of field and armature winding.
- Sparking at the brushes is more.

To overcome the above drawbacks of dc series motor to run efficiently on ac supply following constructional modifications are done.

- Field core is constructed using a material that has low hysteresis losses and it laminated to reduced eddy current.
- The field winding is constructed with small numbers of turns due to this pole area increase and flux density decreases this reduced iron losses and reactive voltage drop.
- The number of armature conductors increases to achieve the required torque with low flux.
- Compensation winding is used to reduced armature reaction and increase commutation.

Advantages of Universal Motor

- Universal motor produced high torque at intermediate speed.
- High speed from above 3600 to 25000rpm.
- High power output in a small size suitable for portable tools.

Disadvantages

- Due to brushes, service requirements are increases.
- Create radio and television interference due to brush sparking.
- Careful balancing must be required during working to reduced vibrations.

Application of Universal Motor

- Universal motors are used in shaving machines, Vaccum cleaners.
- Used in drinking and food mixers, portable drill, sewing machine, in tiles cutter.

MODULE VI

ELECTRICAL TARIFF, WIRING SYSTEMS AND LAMPS

What is Electricity tariff?

The electrical energy that is produced in a power station is delivered to a large number of consumers. The consumers can be convinced to use electrical energy if it is sold at a reasonable price. Here comes the idea of tariffs.

Definition: A tariff is the schedule of rates structured by the supplier for supplying electrical energy to various types of consumers. The rate at which electric energy is supplied to a consumer is known as a tariff.

The following elements are engaged into account to determine the tariff:

- Types of load (domestic, commercial, industrial)
- Maximum demand
- Time at which load is required
- The power factor of the load
- Amount of energy used

The way in which consumers pay for electrical energy changes according to their demands. Industrial consumers consume more energy for the relatively longer period than domestic consumers.

Tariffs should be framed in such a way so that it covers the cost of production, cost of supply, and yet yields some reasonable profit.

The price of energy supplied by a generating station depends on the established capacity of the plant and kWh generated. Maximum demand increases the installed capacity of the generating station.

The instant at which maximum demand occurs is too important in plant economics. If the maximum demand of the consumer and the maximum demand on the system take place simultaneously, additional plant capacity is needed.

However, if the maximum demand of the consumer occurs during off-peak hours, then we just need to improve the load factor and no extra plant capacity is needed. Thus, the overall cost per kWh generated is reduced.

Power factor is likewise an important factor from the point of view of plant economics.

At a low-power-factor, the load current is very high. Therefore, the current to be supplied from the generating station is also large. This high current is also responsible for large I^2R losses in the system and larger voltage drops. **Therefore**, the **regulation** becomes poor; in order to supply the consumer's voltage within permissible limits, power factor correction equipment is to be set up. Therefore, the cost of generation increases.

The cost of electrical energy is reduced by using a large amount of energy for a longer period.

Table 1: Consumers and Their Tariffs

Consumers	Examples	Supply Given	Demand Factor	Tariff
Domestic	Residential load, light, fan, television, radio, electric irons, domestic pumps, coolers, air conditioners	1ϕ: supply up to a load of 5 kW 3ϕ: supply for loads exceeding 5 kW	Small consumers (high unity), big consumers (0.5)	1. Simple 2. Flat rate 3. Block rate
Commercial	Shops, business houses, hotels, cinemas, clubs, etc.	1ϕ: supply up to a load of 5 kW 3ϕ: supply for loads exceeding 5 kW	Fairly high	1. Simple 2. Flat rate 3. Block rate
Agricultural	Tube wells	3ϕ: power up to 20 kW	Unity	Flat rate

Bulk	Railways, educational institutes, the military establishment, hospitals	3ϕ: power at 415 V or 11 kV depending on their requirement, the load exceeding 10 kW		Flat rate
Industrial (small)	Atta chakkis, small workshop, sawmill, etc.	3ϕ: power supply at 415 V, load not exceeding 20 kW	Usually high (0.8)	Block tariff
Industrial (medium)		3ϕ: power supply at 415 V, the load exceeding 20 kW but not exceeding 100 kW		Two-part tariff
Industrial (large)		Power supplied at 11 kV or 33 kV, the load exceeding 100 kW	0.5	KVA maximum demand factor tariff

Objectives of an Electricity Tariff

1. Recovery of cost of producing electrical energy at the power station.
2. Recovery of cost on the capital investment in transmission and distribution systems.
3. Recovery of cost of operation and maintenance of the supply of electrical energy. For example, metering equipment, billing, etc.
4. A suitable profit on the capital investment.

Electricity Tariff Characteristics

1. ***Proper return.*** The tariff should be structured in such a way that it guarantees the proper return from each consumer. The total receipts from the consumers must be equal to the cost of producing and supplying electrical energy plus the reasonable profit.

2. ***Fairness***. The tariff must be fair so that each and every consumer is satisfied with the cost of electrical energy. Thus, a consumer who consumes more electrical energy should be charged at a lower rate than a consumer who consumes little energy. It is because increased energy consumption spreads the fixed charge over a greater number of units. Hence reducing the overall production cost of electrical energy.

3. ***Simplicity***. The tariff should be simple and consumer-friendly so that an ordinary consumer can easily understand.

4. ***Reasonable profit***. The profit element in the tariff should be reasonable. An electric supply company is a public utility company and generally enjoys the benefits of a monopoly.

5. ***Attractive***. The tariff should be attractive so that it can attract a large number of consumers to use electricity.

TYPES OF TARIFF IN ELECTRICITY

Various Types Of Electricity Tariff

1. Simple Tariff

In this type of tariff, a fixed rate is applied for each unit of the energy consumed. It is also known as a uniform tariff. The **rate per unit of energy does not depend upon the quantity** of energy used by a consumer. The price per unit (1 kWh) of energy is constant. This energy consumed by the consumer is recorded by the energy meters.

Graphically, it can be represented as follows:

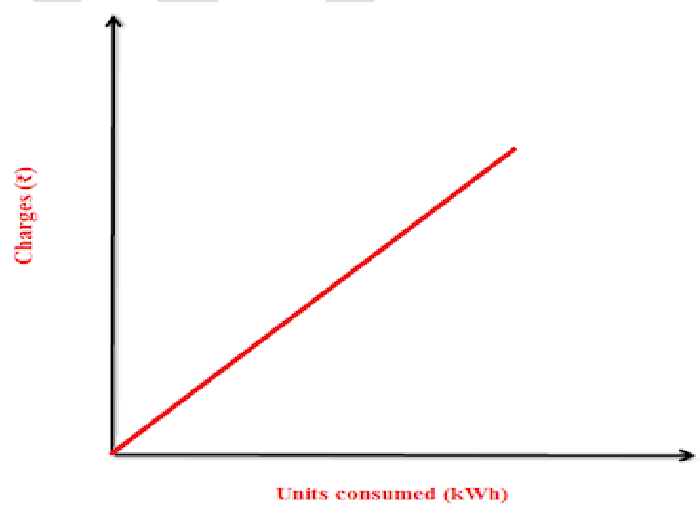


Figure : Simple Tariff

$$\text{Cost/kWh} = \text{Rs.}\frac{\text{Annual fixed cost} + \text{Annual operating cost}}{\text{Total number of units supplied to the consumer per annum}}$$

Advantages:

- Simplest method
- Easily understandable and easy to apply
- Each consumer has to pay according to his utilization

Disadvantages

- There is no discrimination according to the different types of consumers.
- The cost per unit is high.
- There are no incentives (an attractive feature that makes the consumers use more electricity.)
- If a consumer does not consume any energy in a particular month, the supplier cannot charge any money even though the connection provided to the consumer has its own costs.

Application

- Generally applied to tube wells used for irrigation purposes.

2. Flat Rate Tariff

In this tariff, different types of consumers are charged at different rates of cost per unit (1kWh) of electrical energy consumed. Different consumers are grouped under different categories. Then, each category is charged money at a fixed rate similar to Simple Tariff. The different rates are decided according to the consumers, their loads and load factors.

Graphically, it can be represented as follows:

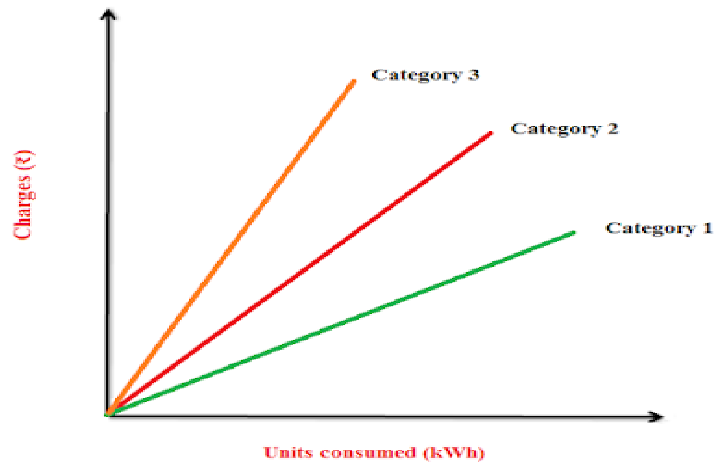


Figure : : Flat Rate Tariff

Advantages

- More fair to different consumers.
- Simple calculations.

Disadvantages

- A particular consumer is charged at a particular rate. But there are no incentives for the consumer.
- Since different rates are decided according to different loads, separate meters need to be installed for different loads such as light loads, power loads, etc. This makes the whole arrangement complicated and expensive.
- All the consumers in a particular "category" are charged at the same rates. However, it is fairer if the consumers that utilize more energy be charged at lower fixed rates.

Application

- Generally applied to domestic consumers.

3. Block Rate Tariff

In this tariff, the first block of the energy consumed (consisting of a fixed number of units) is charged at a given rate and the succeeding blocks of energy (each with a predetermined number of units) are charged at progressively reduced rates. The rate per unit in each block is fixed.

For example, the first 50 units (1st block) may be charged at 3 rupees per unit; the next 30 units (2nd block) at 2.50 rupees per unit and the next 30 units (3rd block) at 2 rupees per unit.

Graphically, it can be represented as follows:

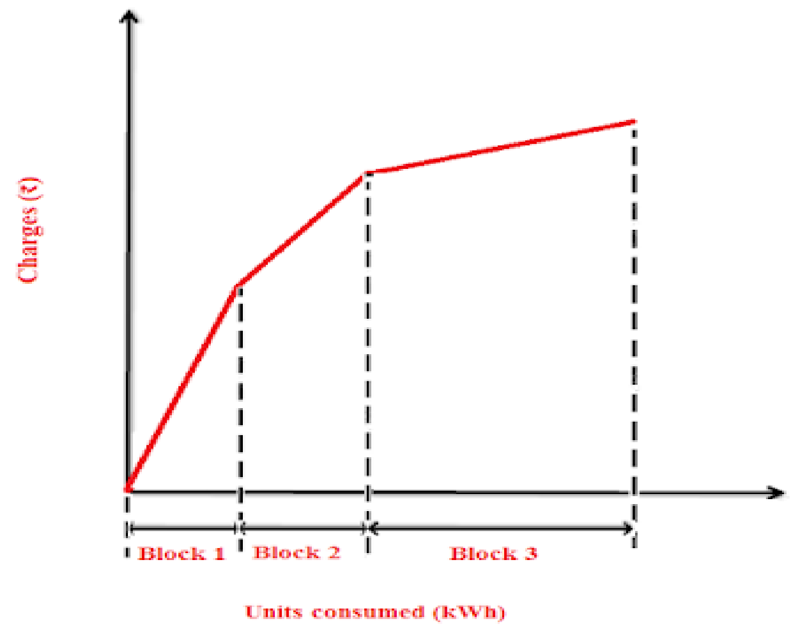


Figure : Block Rate Tariff

Advantages

- Only 1 energy meter is required.
- Incentives are provided for the consumers due to reduced rates. Hence consumers use more energy. This improves load factor and reduces cost of generation.

Disadvantages

- If a consumer does not consume any energy in a particular month, the supplier does not charge any money even though the connection provided to the consumer has its own costs.

Application

- Generally applied to residential and small commercial consumers.

4. Two Part Tariff

In this tariff scheme, the total costs charged to the consumers consist of two components: fixed charges and running charges. It can be expressed as:

Total Cost = [A (kW) + B (kWh)] Rs.

Where, A = charge per kW of max demand (i.e. A is a constant which when multiplied with max demand (kW) gives the total fixed costs.)

B = charge per kWh of energy consumed (i.e. B is a constant which when multiplied with units consumed (kWh), gives total running charges.)

The fixed charges will depend upon maximum demand of the consumer and the running charge will depend upon the energy (units) consumed. The fixed charges are due to the interest and depreciation on the capital cost of building and equipment, taxes and a part of operating cost which is independent of energy generated. On the other hand, the running charges are due to the operating cost which varies with variation in generated (or supplied) energy.

Advantages

- If a consumer does not consume any energy in a particular month, the supplier will get the return equal to the fixed charges.

Disadvantages

- Even if a consumer does not use any electricity, he has to pay the fixed charges regularly.
- The maximum demand of the consumer is not determined. Hence, there is error of assessment of max demand and hence conflict between the supplier and the consumer.

Application

- Generally applied to industrial consumers with appreciable max demand.

5. Maximum Demand Tariff

In this tariff, the energy consumed is charged on the basis of maximum demand. The units (energy) consumed by him is called maximum demand. The max demand is calculated by a maximum demand meter. This removes any conflict between the supplier and the consumer as it were the two part tariff. It is similar to two-part tariff.

Application

- Generally applied to large industrial consumers.

6. Power Factor Tariff

In this tariff scheme, the power factor of the consumer's load is also considered. We know that power factor is an important parameter in power system. For optimal operation, the pf must be high. Low pf will cause more losses and imbalance on the system. Hence the consumers which have low pf loads will be charged more. It can be further divided into the following types:

(I) KVA Maximum Demand Tariff

In this type of tariff, the fixed charges are made on the basis of maximum demand in kVA instead of KW.

We know that power factor = kW / Kva

Hence, the pf is inversely proportional to kVA demand. Hence, a consumer having low power factor load will have to pay more fixed charges. This gives the incentive to the consumers to operate their load at high power factor. Generally, the suppliers ask the consumers to install power factor correction equipment.

(II) KW And KVAR Tariff

In this tariff scheme, the active power (kW) consumption and the reactive power (kVAR) consumption is measured separately. Of course, a consumer having low power factor load will have to pay more fixed charges.

(III) Sliding Scale Tariff

In this type of tariff scheme, an average power factor (generally 0.8 lagging) is taken as reference. Now, if the power factor of the consumer's loads is lower than the reference, he is penalized accordingly. Hence, a consumer having low power factor load will have to pay more fixed charges. Also, if the pf of the consumer's load is greater than the reference, he is awarded with a discount. This gives incentives to the consumers. It is usually applied to large industrial consumers.

7. Three Part Tariff

In this scheme, the total costs are divided into 3 sections: Fixed costs, semi-fixed costs and running costs.

Total Charges = [A + B (kW) + C (kWh)]

Where, A = fixed charges,

B = charge per kW of max demand (i.e. B is a constant which when multiplied with max demand (kW) gives the total fixed costs.)

C = charge per kWh of energy consumed (i.e. C is a constant which when multiplied with units consumed (kWh), gives total running charges.)

Application

- This type of tariff is generally applied to big consumers.

Electricity Tariff Example 1

The maximum demand of a consumer is 15 A at 230 V and his/her total energy consumption is 9000 kWh. If the energy is charged at the rate of Rs. 5 per unit for 600 h use of the maximum demand per annum plus Rs. 2 per unit for additional units, calculate (1) annual bill and (2) equivalent flat rate.

Solution

Assume the load factor and power factor to be unity.

$$MaximumDemand = \frac{230 \times 15 \times 1}{1000} = 3.45kW$$
$$1.\ Units\ consumed\ in\ 600\ h = 3.45 \times 600 = 2070kWh$$
$$charges\ for\ 2070\ kWh = Rs.5 \times 2070 = Rs.10,350$$
$$Remaining\ Units = 9000 - 2070 = 6930kWh$$
$$charges\ for\ 6930\ kWh = Rs.2 \times 6930 = Rs.13,860$$
$$Total\ Annual\ Bill = Rs.(13,860 + 10,350) = Rs.24,210$$
$$2.\ Equivalent\ Flat\ Rate = Rs.\ ^{24,210}/_{9000} = Rs.2.69$$

Electricity Tariff Example 2

A consumer has a maximum demand of 150 kW at 50% load factor. If the tariff is Rs. 800 per kW of maximum demand plus Rs. 2 per kWh, find the overall cost per kWh.

Solution

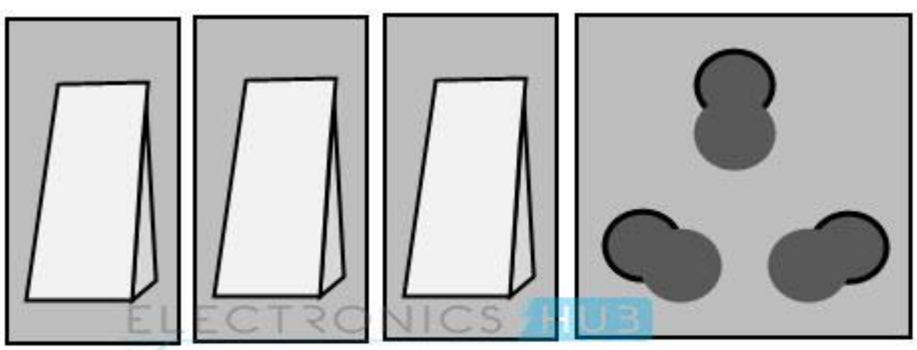
Units Consumed/Year= MD × LF × Hours in a year=150×0.5×8760=657,000

kWhAnnual Charges=Annual MD Charges+Annual Energy Charges=Rs.(150×800+2×657,000) =1,434,000

∴Overall Cost / kWh=Rs.1,434,000657,000=Rs. 2.18

INTRODUCTION TO ELECTRICAL WIRING SYSTEM

The Electrical Wiring Systems are mostly standardized with several rules, regulations and laws. Electrical Wiring must be installed correctly and safely in accordance with electrical regulations and standards. If the electrical wiring is carried out incorrectly or without confirming to any standard, then it may lead to incidents like short circuits, electric shocks, damage the device / appliance or leads to the malfunctioning of device which further causes for the reduction of device life.



Several factors have to be considered before the actual installation work to be done for residential, commercial or industrial wiring. These factors include type of building construction, type of ceiling, wall and floor construction, wiring methods, installation requirements, etc.

Let us discuss some electrical wiring basics, i.e., the concept of electrical wiring, steps involved, methods followed and common types of electrical wiring in brief.

WARNING: This is not a user guide or tutorial on Electrical Wiring. This is just a theory explaining different Electrical Wiring Systems and different possible ways of installing Electrical Wiring. If you are planning a project which involves AC Mains Electrical Wiring, then definitely seek help and guidance from a professional.

Electrical Safety

Before starting any installation work, the first and foremost thing is the concern of safety of the personnel. Electricity is dangerous and direct or indirect contact of electrical equipment or wires with the power turned ON can result in serious injuries or sometimes even causes death. Follow the below steps to maintain the safety at the workplace.

Electrical Safety

1. Always use safety equipment like goggles, gloves, shoes, etc. and avoid any direct contact with live or energized circuits.
2. Have the skills and techniques to distinguish the exposed live parts of the electrical equipment.
3. Disconnect the source supply while installing or connecting wires.
4. The power supplied to the installation must be controlled on the main switchboard, which should consist of circuit breaker.
5. Conductive tools and materials must be kept at a safe distance from live parts of the circuit or equipment.
6. Use non-conductive hand tools for which they are rated to perform electrical work. If they are used for voltage (or current) rating other than rated, the insulation strength of the tool will breakdown and causes electric shock.

Distribution of Electricity

The Electricity Board / Department provides the electric supply up to the outside the consumer's premises (either residential, commercial or industrial). The consumer has to take the connection from that point to the main distribution board / switchboard at home.

From the main switchboard / distribution board, various types of electrical loads such as fans, lights, room coolers, and refrigerators are connected through respective circuits and electrical wiring.

There are different types of wirings used for connecting the loads to the mains, which can be used for house electrical wiring as well as industrial electrical wiring. Some of these are discussed below.

Types of Electrical Wiring Systems

Electrical Wiring is an important part of a building, be it a residential building (individual houses or apartments), large commercial spaces (office buildings) or industries (factories). There are several methods and systems of Electrical Wiring, which are used for lighting and other power circuits.

The type of Electrical Wiring plays a major role in the overall cost of the installation. So, it is very important to understand what type of Electrical Wiring Systems are suitable for a particular job.

Some common factors to be considered while choosing a particular Electrical Wiring System are:

- Cost of the Wiring System
- Type of Wires / Cables used
- Quality of the Wires
- Type of load (light, HVAC, motors etc.)
- Safety of the Wiring System
- Possibility of future modifications / extensions
- Life of installation
- Construction of the building (wooden, concrete, brick and mortar, etc.)
- Fire safety

Irrespective of the type of Wiring and the choice of Wire, the Electrical Wiring System should be able to protect against regular mechanical wear and tear under normal operating conditions.

Usually, the type of wire determines the Electrical Wiring Systems (or at least their classification). Some of the commonly used Electrical Wiring Systems in Residential, Commercial, Industrial, Auditoriums, etc. are:

- Cleat Wiring
- Casing and Capping Wiring
- Batten Wiring (CTS or TRS)

- Conduit Wiring (Surface or Concealed)
- Lead Sheathed Wiring

Let us now take a look at these Wiring Systems / Installations one by one.

Cleat Wiring

In this, porcelain, wood or plastic cleats are fixed to walls or ceilings at regular intervals, i.e., 0.6 m between each cleat. PVC insulated cables are taken through the holes of each cleat and hence, the cleat supports and holds the wire.

This is an inexpensive method of wiring and is used for temporary installations. Therefore, it is not suitable for home electrical wiring and also it is an outdated method.

Casing and Capping Wiring

In this, cable is run through a wooden casing having grooves. The wood casing is prepared in such a way that it is of a required fixed length with parallel grooves that accommodates the cables. The wooden casing is fixed to the walls or ceiling with screws.

After placing the cables inside the grooves of casing, a wooden cap with grooves is placed on it to cover the cables. This is also a cheap wiring system, but there is a high risk of fire in case of short circuits.

Batten Wiring

In this, insulated wires are run through the straight teak wooden battens. The wooden battens are fixed on the ceilings or walls by plugs and screws. The cables are fitted onto the battens by using tinned brass link clips.

These clips are fixed to the battens with rust-resistant nails. This wiring installation is simple and cheap as compared to other electrical wiring systems also takes less time to install. These are mainly used for indoor installations.

In this type of wiring, Cabtyre Sheathed Wire (CTS) or Tough Rubber Sheathed Wire (TRS) is generally used as the electrical conductor.

Conduit Wiring

In this wiring, PVC cables are taken through either PVC conduit pipes or through steel conduit pipes. This conduit wiring can be either surface conduit wiring or concealed conduit wiring.

If the conduit pipes are run on surface of the walls and ceilings, it is called a surface conduit wiring. If the conduits are run inside the surface of the walls and ceilings and are covered with plastering, it is called as concealed conduit wiring.

Surface conduit wiring is used in industries to connect the heavy motors. On the other hand, concealed wiring is the most popular and common method of wiring the residential buildings. The conduit wiring is the safest method of wiring and also looks beautiful (concealed conduit wiring).

Lead Sheathed Wiring

This wiring method is also similar the CTS / TRS Wiring except for the type of wire / cable. In this, the electrical conductor is first insulated with Vulcanized Indian Rubber and then it is covered with a sheath of Lead-Aluminum alloy (95% Lead and 5% Aluminum).

Similar to the Batten Wiring, this wiring is also run on wooden batten and are fixed with tinned clips.

Types of Drawings

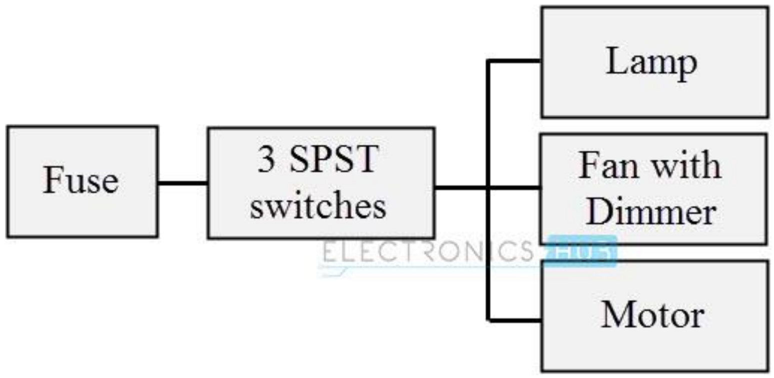
Electrical Drawings plays an important role in electrical installation works as they convey information about connection of various devices and equipment with mains. The information on drawings provides the complete design or plan of electrical installation and also helps to assemble the various equipment.

Some of the electrical wiring diagrams are discussed below. Before knowing about these diagrams, first you must be aware of and have an idea about various symbols used while preparing drawing and also for understanding the wiring connections.

Block Diagram

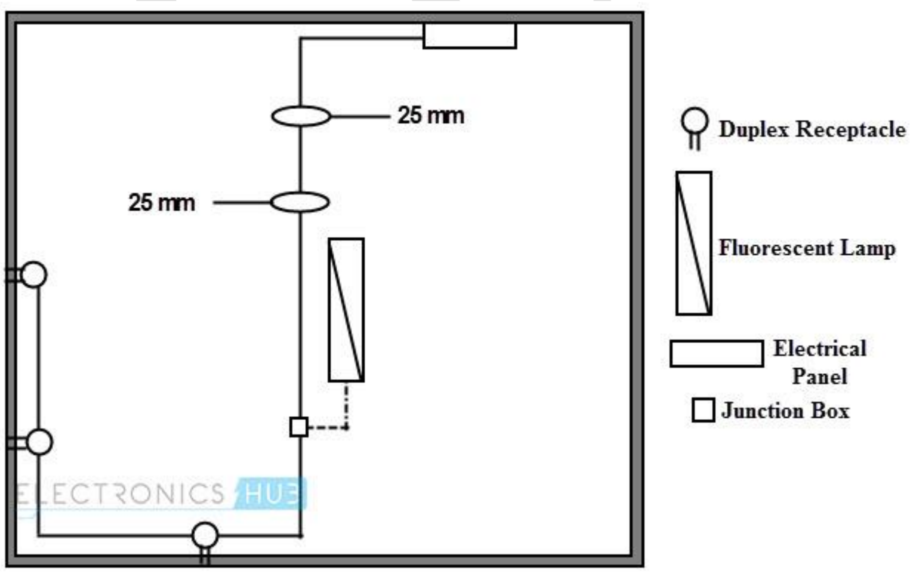
It is a functional drawing which shows and describes the main operating principles of the equipment or devices. It consists of principle functions or parts represented by blocks and are connected through lines that show the relationship between the blocks.

This diagram is usually drawn before implementing a circuit diagram. It will not give any detailed information about the system and also leaves the information about smaller components. And hence, most technicians have limited interest about this diagram.



Circuit Drawing (Diagram)

In this, electrical circuit is graphically represented in a simplified manner. It includes the position information (in mm, cm or m) of various elements like light fixtures, receptacle boxes, junction boxes, ceiling fans, etc.



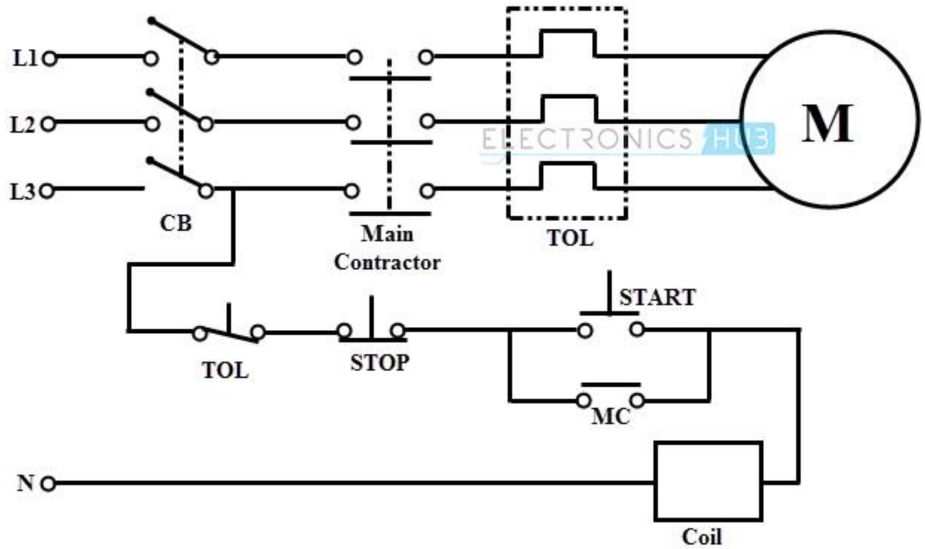
Line Diagram

It is a simplified notation of an electrical system, also called as One-Line Diagram or Single Line Diagram. It is similar to the block diagram except that various electrical elements such as transformers, switches, lights, fans, circuit breakers, and motors are represented by standard schematic symbols.

It consists of symbols to represent the components and lines to represent the wires or conductors which connects the components together.

The line diagram is actually derived from the block diagram. It doesn't give any layout of the parts and their detail wiring information of the components.

However, you can do wiring by following the information given in this diagram. These diagrams are usually intended to illustrate the working of an electric circuit.

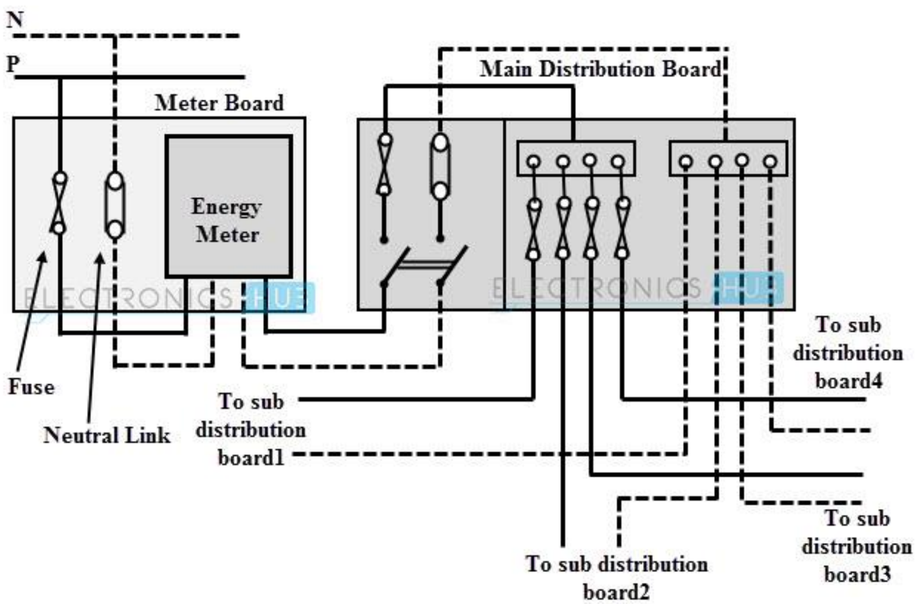


Wiring Diagram

The electrical wiring diagram is a pictorial representation of the circuit, which shows the wiring between the parts or elements or equipment.

It gives detailed information about wiring such that one can get an easy idea of making connection between the devices. It includes relative position, arrangement of the devices and also terminals on the devices.

It shows power supplies and earth connections, control and signal functions (with simplified shapes), termination of unused contacts and leads, interconnection via plugs, blocks, sockets, terminal posts, lead-through, etc.



Wiring Schedule

It is a list of cables or wires used in the installation with its reference number, length, type and the amount of insulation stripping required for soldering the cable. It gives the raceways of the wire and also starting and termination points.

In some complex equipment, wiring table gives the interconnection of the equipment (such as motors and heaters) with starting and finishing reference points. It also includes the wire identification markings, wire colors, size and so on.

Schedule:		Motor Control			
Wire No	**From**	**To**	**Type**	**Length**	**Strip Length**
1	TB 1/1	CB1/1	16/0.2	600 mm	12 mm
2	TB 1/2	CB1/2	16/0.2	650 mm	12 mm
3	TB 1/3	CB1/5	16/0.2	600 mm	12 mm
4	TB 1/4	MC/A1	16/0.2	800 mm	12 mm
5	TB 1/5	CH/1	16/0.2	500 mm	12 mm

Parts List

Although it is not a drawing, parts list is an integral part of drawing, which defines the various symbols and parts used in other drawings such as wiring diagram, line diagram and block diagram.

It gives the information on the type of circuit component with their reference numbers. This list is useful for identifying, locating and cross referencing the actual component labeled or given in other electrical drawings in order to ensure the choice of appropriate parts before doing the electrical wiring.

Part List ELECTRONICS HUB

Ref	BIN	Description	Part No
CB	A3	Circuit Breaker	PKZ 2 /ZM-40-8
MC	A4	Contactor	DIL 2AM 415/50
TOL	A4	Overload Relay	Z 1-63

Wiring Preparation

As we are discussing the sequence of steps in wiring like understanding the safety, knowing types of wiring systems, understanding the difference among various electrical drawings and symbols, the next step of electrical wiring process is the preparation of wires or cables and electrical tools.

The wiring preparation includes the following considerations.

1. The type of conductor can be single solid wire or stranded wire conductor (which is made up of a number of thin stands). Single solid wires are not flexible and are used where rigid connections are required such as power switching contractors. Mostly stranded conductors are preferred for electrical installations.

2. The specifications of the wire depend on the several factors like number of strands in the conductor, insulation type, cross section area of the wire, diameter of the strands, etc.

3. Choose the wires depends on the color code mentioned by various standards such as brown for phase wire, blue for neutral, green for earth and so on. Click here to know briefly about the electrical wiring colors of the wires or cables.

4. Various basic electrical tools are required to do the installation work and some of these tools include cutter, strippers, testers, pliers, etc. These tools are explained in our earlier articles, so please check those electrical tools by clicking here.

5. Choose the components such as electrical boxes, switches, receptacles, etc. based on their size and rating.

Start wiring the components together by following the wiring diagrams. Once components, tools and cables are selected, by considering and following the safety of personnel as well as equipment, proceed with installation.

Types of Electrical Wiring

We know that electrical circuit is a closed path through which electricity flows from phase or hot wire to the device or apparatus and then back the source though neutral wire.

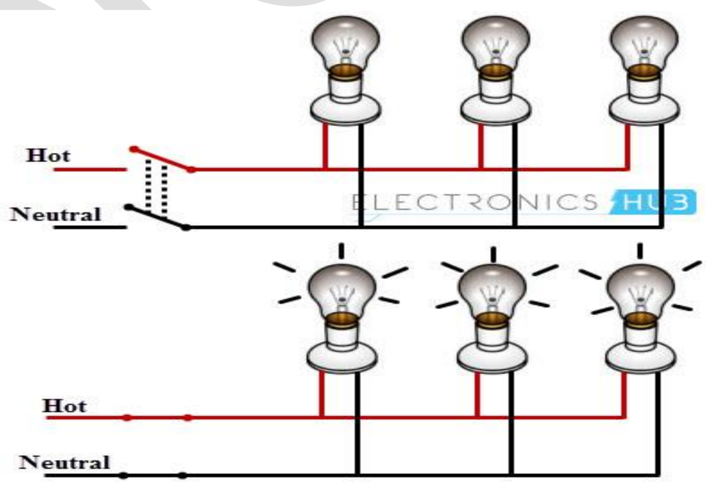
Along the way, the electricity path may consist of fixtures, switches, receptacles, junction boxes, etc. So, the wiring may be routed through these elements before actually making connections with apparatus or device.

Majorly, the wiring is divided into two types depending on the way the devices are powered or connected to the supply. They are:

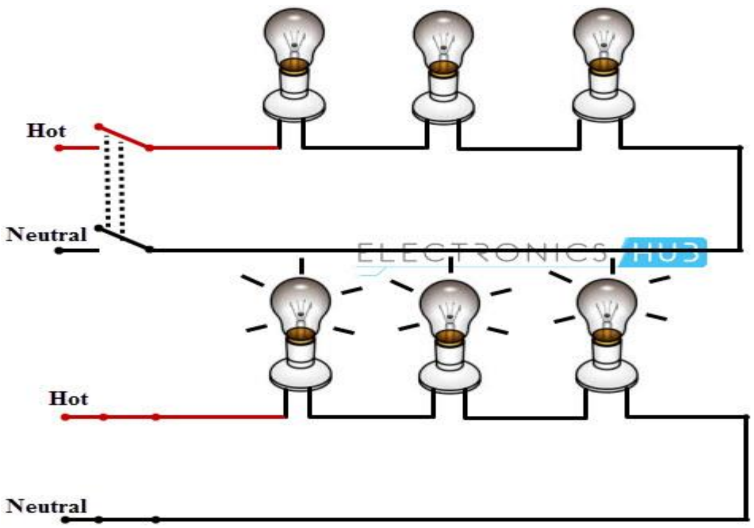
- Parallel Wiring
- Series Wiring

In Parallel Wiring, several devices on the installation are powered on a single circuit. It is the most accepted wiring in homes and industries, in which devices are connected in parallel with the supply source as shown in figure.

In this, both phase (or hot) and neutral cables are routed through the electrical boxes (junction boxes) from which individual receptacles, fixtures, and devices are branched.



The Series Wiring is the rarely used wiring in which hot wire is routed through the several devices and then last device terminal is connected to the neutral wire. It is like an old Christmas lights or serial lights wiring in which one light burnout leads to the shutdown of the entire network.

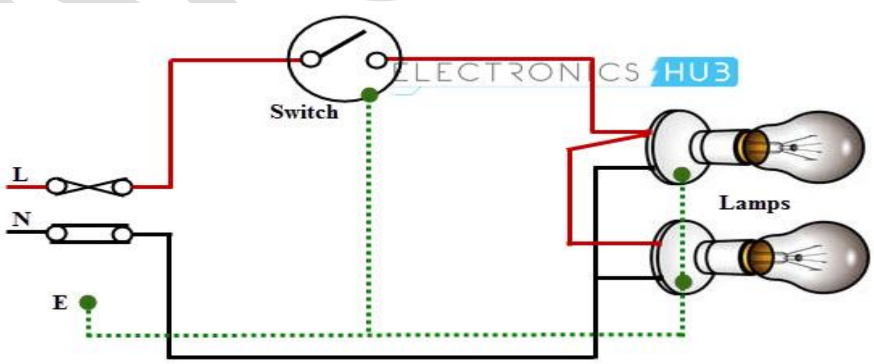


Examples of Electrical Wiring

For a better understanding of the wiring concept, here we are giving some examples of the wiring circuits, which are commonly used in our homes / offices.

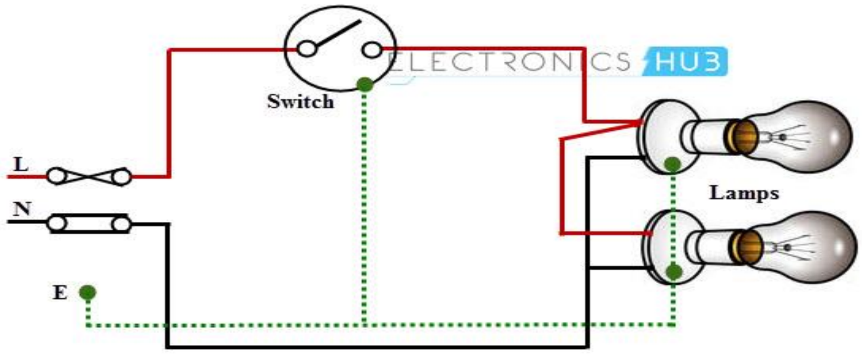
Single Bulb (or any other load) Controlled by a One Way Switch

In this, hot wire is connected to the one terminal of the switch and other terminal of the switch is connected to the bulb positive terminal, then bulb negative terminal is connected to the neutral wire as shown in figure.



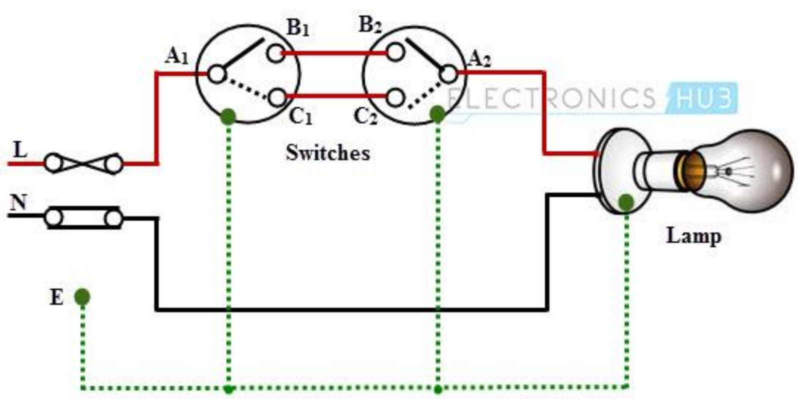
Two Blubs Controlled by a One Way Switch

In this, two bulbs are connected in parallel with the supply wires (phase and neutrals), which are routed by single one-way switch as shown in figure.



Single Blub Controlled by Two Way Switches

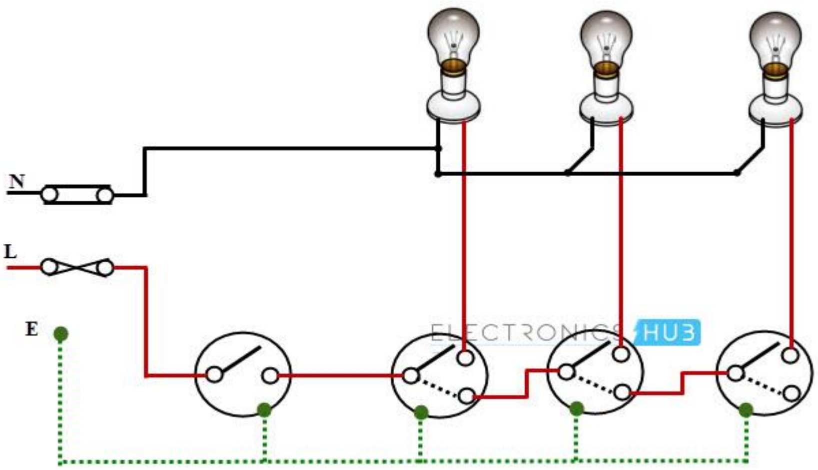
This wiring is also called as Staircase Wiring. In this, a light bulb / lamp is controlled from two different places / sources by using two two-way switches. This type of wiring is used in bed rooms to switch ON/OFF the lamp from two sources (at the bed side and at switchboard). The connection of switches with the lamp is shown below.



Warehouse Wiring

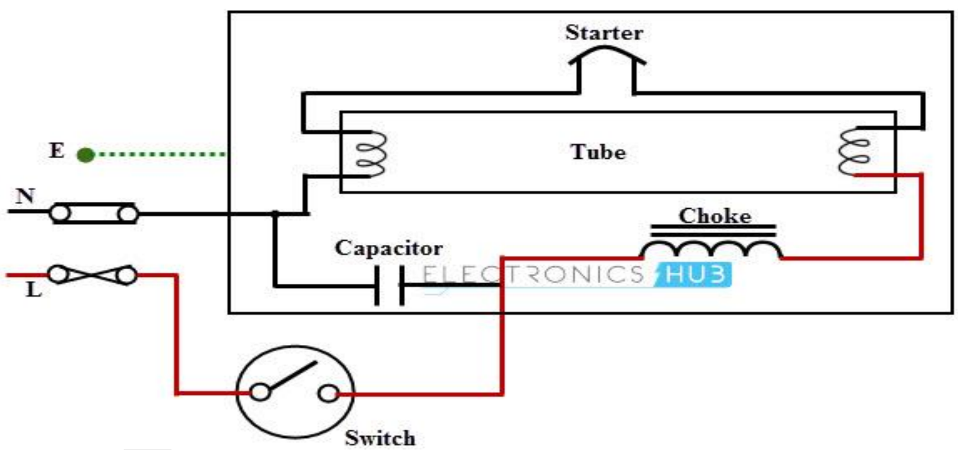
This type wiring is used in big godowns, long passages, warehouses and tunnel like structures having many rooms or portions. It follows the linear sequence for switching the lights from one end to the other.

When a person leaves one room and enters the next, turning the light switch makes previous room's lamp to be switched OFF, while the present room lamps to be switched ON. It turns OFF one lamp while switching ON the another. The schematic wiring diagram for warehouse wiring is shown in below.



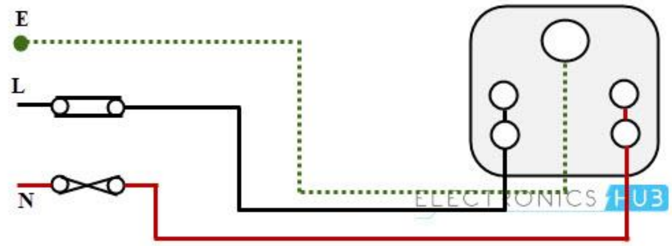
Fluorescent Lamp Controlled by a One-Way Switch

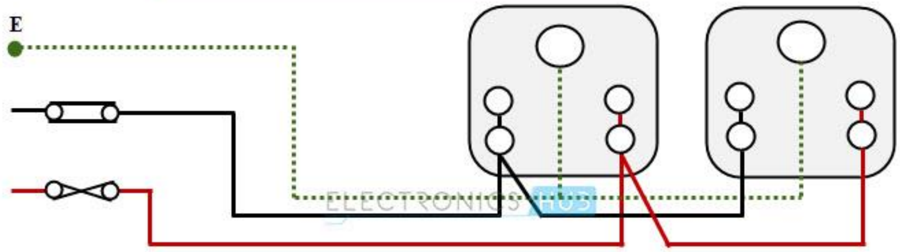
The switching of fluorescent lamp with single one-way switch through ballast and capacitor is shown in below figure. In this, phase wire is connected to the one end of the switch and another end of the switch is connected to the choke (or ballast). One electrode of the lamp is connected to the choke and other to neutral terminal as shown in figure.



Socket Outlet Wiring

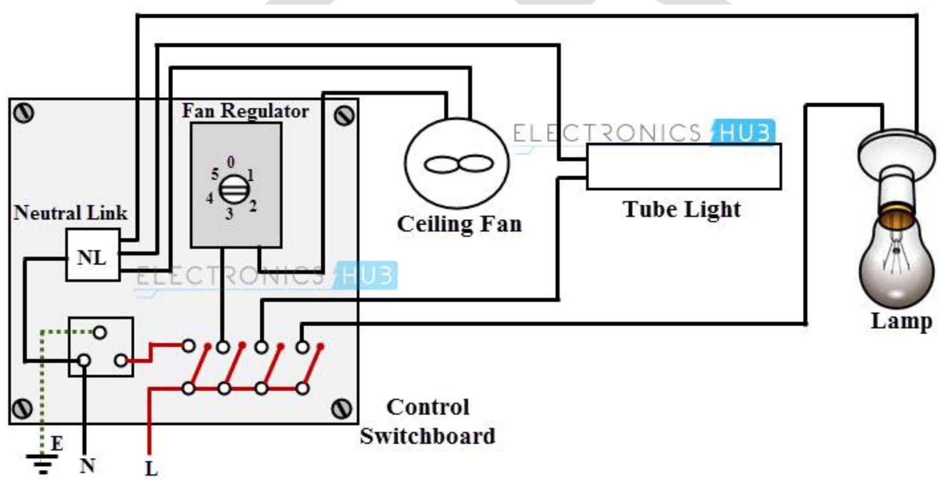
The outlet holds a plug and passes the current through it when the power is routed to the socket through a switch. The single socket connection and radial socket connection are shown in below figure.





Control Switch Board Wiring

The schematic diagram for a control switch board is shown in the below figure. In this, a ceiling fan, a fluorescent lamp and a light bulb are controlled by appropriate switches.



HOW TO WIRE A DISTRIBUTION BOARD?

Distribution Board aslo know as "Panel Board", "Switch & Fuse Board" or "Consumer Unit" is a box installed in the building containing on protective devices, such as circuit breaker, fuses, isolator, switches, RCDs and MCBs etc. The electric main supply (230V AC & 120V AC in US) is connected through secondary of the transformer (3, Phase 4 Wire System), single phase energy meter and MCBS (DP & SP) to Sub Circuits and Final Sub Circuits to protect all the connected electrical devices and appliances through electrical Wiring installation.

- Related Wiring Tutorial: Wiring of the Distribution Board with RCD (Single Phase

Supply From Utility Pole & Energy Meter to the Consumer Unit)

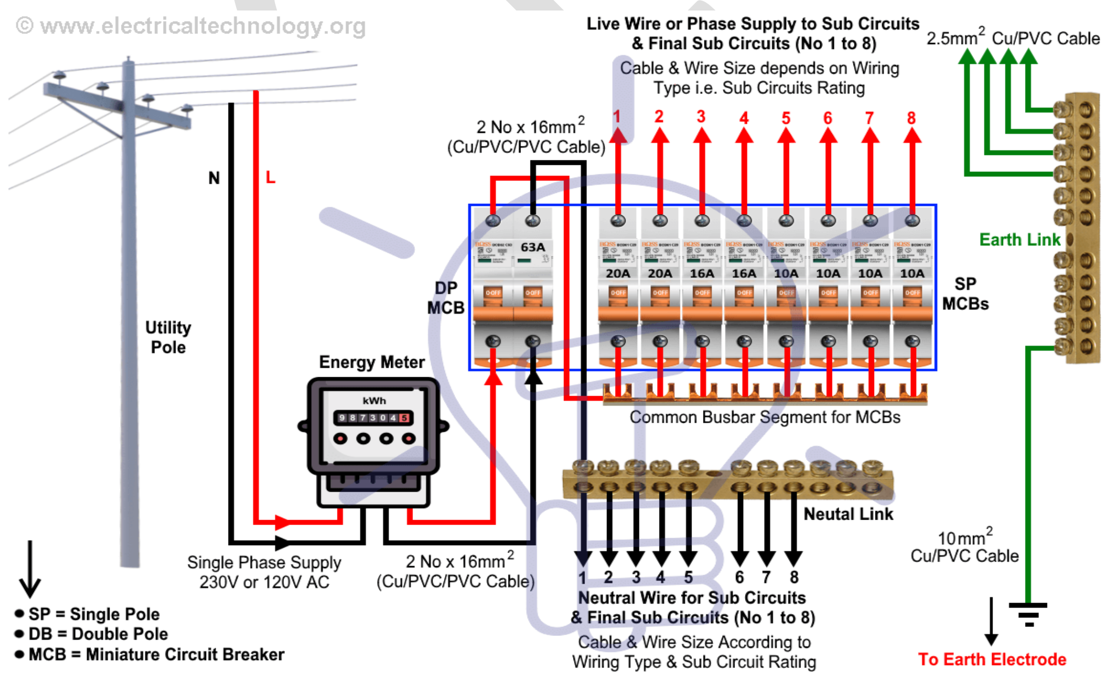
In the following single phase electrical wiring for home supply, We used 63A MCB (DP), 63A RCD (DP) and different rating if MCBs (SP) such as 20A, 16A, 10A etc according to your need.

In the fig below for single phase electric home supply installation and wiring of a distribution board, you may see the the single phase electric supply (230V AC and 120V AC for US) service mains i.e. Line (Red) and Neutral (Black) carrying single phase supply from transformer secondary and utility pole (3 Phase, 4 Wire (Star) System) to the single phase energy meter.

Both the Live and Neutral wires go to the Main Double Pole Circuit breaker. The Live from DP MCB then connected to the common busbar segment for MCBS which is directly connect to the Single Pole Circuit breaker. The outgoing of the SP MCBS are connected to the sub circuits, final sub circuits and electrical devices and appliances then.

The Neutral from the Main DP MCB is connected to the Neutral Link and the outgoings wires are connected to the sub, final sub circuits and electrical appliances. Keep in mind all the electrical devices and appliances should be connected to the Earth Link for safety which is directly connected to the earth electrode and earth plate for proper earthing and grounding.

Below is a Wiring diagram of the distribution board , Single phase electric supply from electric pole and Energy meter to the main distribution board (Without RCD = Residual Current Devices).



Wiring of the Distribution Board (Single Phase Supply)
(From Utility Pole & Energy Meter to the Consumer Unit)

While we have already discussed the distribution board, types of distribution boards such as Main Distribution Board (MDB), Sub Distribution Board (SDB), Final Distribution Board (FDB), Sub Circuits and Final Sub Circuits in the previous post, Therefore, We will only discus the main electrical wiring accessories used in this basic Single Phase Home Supply Main Distribution Board Installation.

Wiring Color Code:

We have used **Red** for **Live** or **Phase** , **Black** for **Neutral** and **Green** for Earth Wire. You may use the specific area codes i.e. **IEC – International Electrotechnical Commission** (UK, EU etc) or **NEC (National Electrical Code** [US & Canada] where;

NEC:

Single Phase 120V AC:

Black = **Phase** or **Line**, **White** = **Neutral** and **Green**/**Yellow** = **Earth Conductor**

Three Phase 208 AC:

Black = **Phase 1** or **Line1**, **Red**= **Line 2, Blue= Line 3, White / Gray =**
Neutral and **Green**/**Yellow** = **Earth Conductor**

IEC:

Single Phase 230V AC:

Brown= **Phase** or **Line**, **Blue**= **Neutral** and **Green** = **Earth Conductor**

Three Phase 208 AC:

Grey= **Phase 1** or **Line1**, **Black**= **Line 2, Brown= Line 3, Blue =**
Neutral and **Green**= **Earth Conductor**

Requirement to Wire a Single Phase Distribution Board

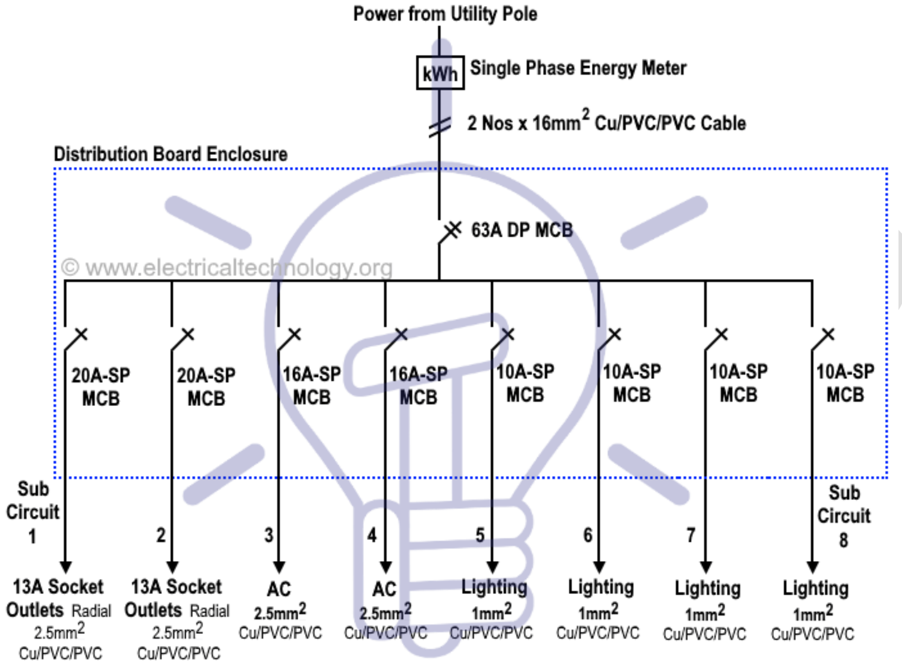
- *DP = Double Pole MCB (The main isolator or main switch).*
- *SP = Single Pole MCB (Circuit Breakers and Fuses).*
- *MCB & CB = Miniature Circuit Breaker and Circuit Breaker.*

DP = Double Pole MCB (The Main Switch)

This allows you to turn OFF and ON the electric supply to your home as it is is the main operating switch to control & manage the flow of electric supply in the wiring system. By using the Main Switch, you may be able to immediately switch OFF the electric supply in the home in case of emergency i.e. electric shock, fire, short circuit or while working on main board to troubleshoot or maintenance of the system. Multiple Main switch and fuse board can be used in case of many supply units i.e. for different floors etc.

(CB) Circuit Breakers (SP)

Circuit breaker is a device which switch OFF the circuit from electric supply at abnormal and make the circuit in normal conditions same as fuse. These are automatic protection devices in the Main switch board or fuse-box that switch off a circuit if they detect a fault. the size of the fuse and Circuit Breaker are similar, but using circuit breaker instead of fuse make sense due to automatic operation. In addition, you may be able to reset it again if it trips ever.



Electrical Wiring Diagram of a 230V Single Phase, 63A Distribution Board (Consumer Unit) for Lighting, AC Units & 13A Radial Circuits

ELECTRICAL EARTHING

Earth is used as an electrical conductor for electricity by man over 270 years back. The other name for Electrical Earthing is Grounding. Electrical earthing is done to protect ourselves from shock during fault conditions. The common electrode used for Earthing is copper, which is used for grounding. The basic requirement of every household or industry is to maintain proper Earthing. The main purpose of the grounding or earthing systems is to provide a reference to the earth. Let us discuss in detail about what is Earthing, why it is required, how Earthing should be done, different types of Earthing and its advantages.

What is Earthing or Grounding?

The safety measures to be taken by connecting any equipment conductive surfaces with Earth Potential is termed as Earthing. Electrical Earthing is shown in the figure.

Earthing

- In an electrical system, the parts of the equipment connected with the Earth's conductive surface for safety is known as earthing.

Why Earthing is Required?

- During the normal operations rise in potential is one of the main important aspects where the reference to the earth is properly connected. The earthing or grounding provides the very least resistance through which the fault currents are diverted.
- The currents other than the permissible values will be diverted into the ground. The grounding is the difference of the rise in potential between the equipment and the earth.
- The rise in potential can be between the person and the ground or appliance and the earth or appliance to appliance. Proper earthing can limit the differences in potentials between equipment and earth.
- The grounding or earthing limits the voltage rise or potential difference observed on a supply system. In case if there is a lightning strike on the building or on the power distribution towers, the overvoltages which are developed should be safely contacted through the connection to the ground equipment.
- There are some faults occurring normally in power systems like L-G, L-L, L-L-L, and L-L-L-G. Among these L-G and L-L-L-G faults are diverted into the earth. Electrical Earthing provides a protective layer where the fault current is diverted into the earth.

Protective Earthing

- Protection of devices is done by electrical earthing where the visible conductive surface of appliances or devices is made close to the earth's potential in failure case. Protective earthing is shown in the figure.

Protective Earthing

- In the case of a fault, fault current flows from the equipment to earth to protect against electric shock. The protective devices like fuses, circuit breakers detect the fault and interrupts the supply during fault conditions.
- Though these protective devices isolate the circuit their operating level is too high. So, the Impedance of connection to earth is kept low compared to the normal circuit to divert fault current to earth.

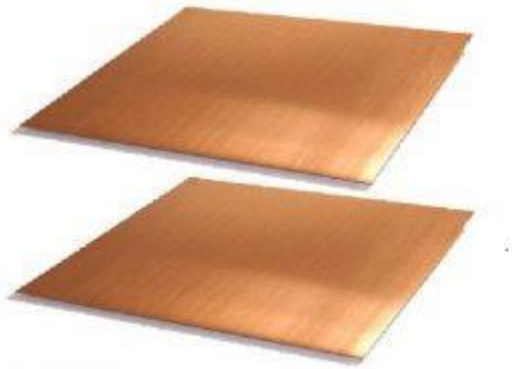
Types of Earthing?

There are different types of earthing system mostly used. They are

- Plate earthing
- Pipe earthing
- Rod earthing

Plate Earthing

- The plate material is of either copper or galvanized iron is used in the plate earthing system. This plate selected should of certain specified dimensions, which is placed inside the earth at a depth less than 3 meters from the bottom. This plate is connected to the electrical conductors to divert the electric charge inside the earth. The diagram of Plate Earthing is given below.



Earthing plate

Pipe Earthing

- A galvanized iron pipe is selected should be such that it has holes pierced at regular intervals and the pipe is narrow at the bottom end.
- A clamp is attached to the G.I pipe to which an earth wire is connected. This pipe diverts the electrical conductance inside the earth. Pipe Earthing is shown in the figure.

Earthing pipe

- The pipe is placed in the earth pit at a depth not less than 3 meters. The space inside the G.I pipe is filled by the alternate layers of salt and charcoal up to the clamp level.
- The top portion of the G.I pipe is left open for maintenance when required by constructing a chamber with bricks. Water is poured into the G.I pipe to maintain

earthing resistance within the specified limits.

- A galvanized steel and a pipe that has holes at regular intervals are kept inside the earth. Keeping in view its low-cost Pipe earthing is commonly used for all domestic purposes.

Rod earthing

This type of earthing is similar to pipe earthing, but a rod made of galvanized steel is used in this case. The rod used for this purpose is buried inside the earth at a certain depth. As it is of low resistive material, the short circuit current will be diverted to the ground safely. The rod earthing diagram is given the following figure.

Earthing rod

Difference Between Pipe and Plate Earthing

The basic difference between pipe and plate earthing is

- In plate earthing, the plate is connected to the electrical conductors to discharge to the earth whereas, in Pipe earthing, the Galvanised Iron pipe is connected to electrical conductors to discharge to the earth.

Advantages of Pipe Earthing over Plate Earthing

- In plate earthing, we use copper which is of the high cost. So, the Galvanised Iron pipe which is of less cost is preferred than plate earthing.
- It requires less maintenance.

Applications of Electrical Earthing at Low Voltage Systems

- The low voltage system consumption appliances are available at the domestic users where proper electrical earthing is done to protect the electrical appliances and also protect ourselves against electric shocks.

- For domestic users, the common fault that occurs is due to voltage fluctuations. During voltage fluctuations proper electrical earthing plays a key role.
- In high voltage system (>1kv) the focus of the earthing system is less on safety but it is more important to look after the reliability of power supply, protection of equipment. The most common type of fault is the L-G fault in the high voltage system. During the L-G fault, the fault current path is closed through the earth.

Therefore, this is all about what is Earthing? It is basically done to protect ourselves from electric shocks. This article discusses an overview of the safety measures to be taken by connecting any equipment conductive surfaces to the Earth which is termed as Earthing. And also we have discussed why earthing is required, protective earthing, different types of earthing and the difference between them, and applications.

PROTECTION DEVICE

Types of Protection Devices

Protection devices for electrical circuits accomplish two main functions namely consistency as well as protection. Protection is assured through detaching power supply in a circuit through **overcurrent protection**, which removes fire hazards and electrocution. Additionally, the accurate protection may be required to obey with organization principles for some products. Designers must take time to know the different protection devices for circuits. Protection devices used to protect circuits from extreme voltages or currents. This article discusses what is a protection device, and types of protection devices used in electrical and electronic circuits.

What is a Protection Device?

The circuit protection device is an electrical device used for preventing an unnecessary amount of current otherwise a short circuit. To ensure the highest security, there are many protection devices available in the market which offers you a total range of protection devices for circuits such as a fuse, circuit breakers, RCCB, gas discharge tubes, thyristors, and more.

Different types of Protection Devices

The different types of **circuit protection devices examples** include the following.

- Fuse
- Circuit Breaker
- PolySwitch

- RCCB
- Metal Oxide Varistor
- Inrush Current Limiter
- Gas Discharge Tube
- Spark Gap
- Lightning Arrester

Types of Circuit Protection Devices

Fuse

In electrical circuits, a fuse is an electrical device used to protect the circuit from overcurrent. It consists of a metal strip that liquefies when the flow of current through it is high. Fuses are essential electrical devices, and there are different types of fuses available in the market today based on specific voltage and current ratings, application, response time, and breaking capacity.

The characteristics of fuses like time and current are selected to give sufficient protection without unnecessary disruption. Please refer to the link to know more about: Different Types of Fuses and Its Applications

Fuse

Circuit Breaker

A circuit breaker is one kind of electrical switch used to guard an electrical circuit against short circuit otherwise an overload which will cause by excess current supply. The basic function of a circuit breaker is to stop the flow of current once a fault has occurred. Not like a fuse, a circuit breaker can be operated either automatically or manually to restart regular operation.

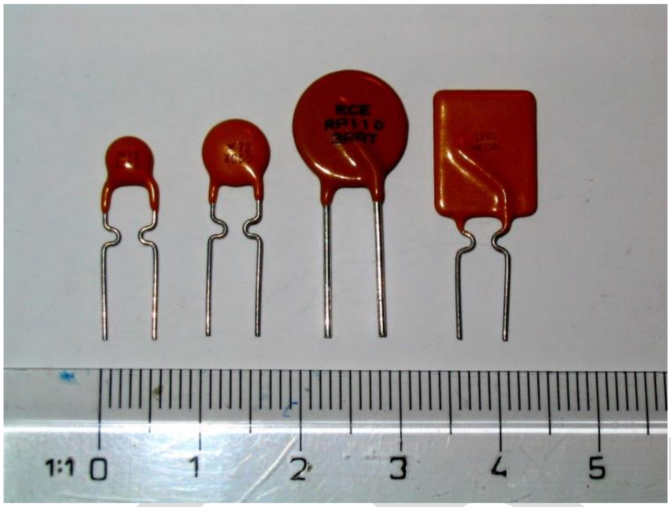
Circuit breakers are available in different sizes from small devices to large switch gears which are used to protect low current circuits as well as high voltage circuits. Please refer the link to know more about: Types of Circuit Breaker and Its Importance

Circuit Breaker

Poly Switch or Resettable Fuse

A resettable fuse is a passive electronic component used for protecting electronic circuits from over-current mistakes. This device is also called as a poly switch or multi fuse or poly fuse. The working of these fuses is same as PTC thermistors in particular situations, however, work on mechanical transforms instead of charge-carrier-effects within semiconductors.

Resettable Fuses are used in several applications like power supplies in computers, nuclear or aerospace applications where substitution is not easy.



Polyswitch

RCCB or RCD

The RCD-residual current device (or) RCCB- residual current circuit breaker is a safety device which notices a problem in your home power supply then turns OFF in 10-15 milliseconds to stop electric shock. A residual current device does not give safety against short circuit or overload in the circuit, so we cannot change a fuse instead of RCD.

RCDs are frequently incorporated with some type of circuit breaker like an MCB (miniature circuit breaker) or a fuse, which guards against overload current in the circuit. The residual current device also cannot notice a human being due to by mistake touching both conductors at a time.

These devices are testable as well as resettable apparatus. A test button securely forms a tiny leakage condition; along with a reset button again connects the conductors after an error state has been cleared.

RCCB

Inrush Current Limiter

This is one type of electrical a component used to stop inrush current for avoiding regular damage to apparatus and evade tripping circuit breakers and blowing fuses. The best examples of inrush current limiter device are Fixed resistors as well as NTC thermistors.

They present a high resistance firstly, which stops huge currents from flowing by turn-on. Because the flow of current will continues, NTC thermistors heat-up, permitting high flow of current throughout normal operation. These thermistors are generally much superior to measurement kind thermistors, which are intentionally planned for power applications.

Inrush Current Limiter

Lightning Protection

The **lightning protection** includes MOV (metal oxide varistor) and gas discharge tube

Metal Oxide Varistor

A varistor or VDR (voltage dependent resistor) is an electronic component and the resistance of this is changeable and depends on the applied voltage. The term varistor has been taken from the variable resistor. When the voltage of this component increases then the resistance decreases. In the same way, when an extreme voltage increases then the resistance will decrease significantly.

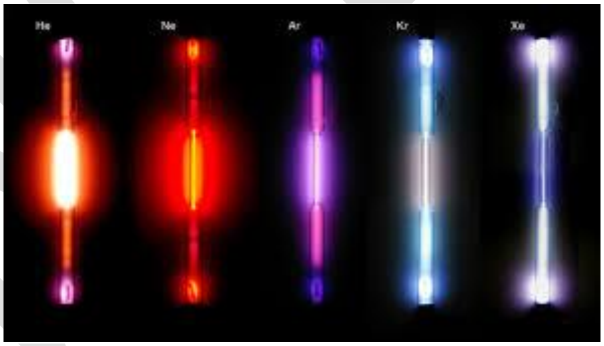
This performance creates them appropriate to guard electrical circuits throughout voltage flows. Origins of a flow can comprise electrostatic discharges as well as lightning strikes. The most frequent type of voltage-dependent resistor is the MOV (metal oxide varistor). Please refer the link to know more about varistor/voltage-dependent resistor circuit with working

Gas Discharge Tube

A gas discharge tube or gas-filled tube is a collection of electrodes in a gas inside a temperature resistant envelope and insulating. These tubes use phenomena allied to electric discharge within gases, also work through ionizing the gas by an applied voltage enough to reason electrical conduction through the fundamental phenomena of the Townsend expulsion.

An expulsion lamp is an electrical device which uses a gas-filled tube such as metal halide lamps, fluorescent lamps, neon lights, and sodium-vapor lamps. Specific gas-filled tubes namely thyratrons, ignitrons, and krytrons are employed as switching devices in various electrical devices.

The required voltage to begin and maintain discharge is reliant on the force, geometry of the tube, and composition of the fill gas. Even though the cover is normally glass, power tubes frequently employ ceramics, as well as military tubes frequently employ glass wrinkled metal.



Gas Discharge Tube

Crowbar vs. Clamping

The terms **Crowbar vs. Clamping** is regularly used to explain how overvoltage protection devices work in a temporary event. A crowbar protection device decreases the voltage under the system's operating voltage. As the impermanent is complete, the crowbar device retunes and lets the circuit to function usually. Throughout a temporary occurrence, a clamping device grasps the voltage just higher than the operating voltage of the system.

ESD Protection

This device protects an electrical circuit from an ESD (Electrostatic discharge), in order to avoid a breakdown of a device. Murata has a wide array of ESD protector devices comprising particular devices very small devices, for high-speed communication, & included noise filters. **ESD Protection** devices can also be utilized to change Zener diodes (TVS), varistors, as well as suppressors.

ESD Protection

Surge Protection Device

The term SPD stands for Surge Protection Device is one type of component used in an electrical fitting security system. The SPD device is allied in parallel in the power supply circuit, which can be used on all stages of the power supply system. The **surge protection device** is the most frequently used and also well-organized kind of over-voltage **protective devices**.

Surge Protection Device

This is all about protection device and its types. The protection of the circuit can be done by using different protection devices in an electrical circuit purposely in order to stop extreme amounts of current. To make sure extreme safety, this article gives an overview of **circuit protection techniques**, namely circuit breakers, **ESD protection** electronic fuses, gas discharge tubes, thyristors, and many more.

DIFFERENT TYPES OF LAMPS AND THEIR APPLICATIONS

What is a Lamp?

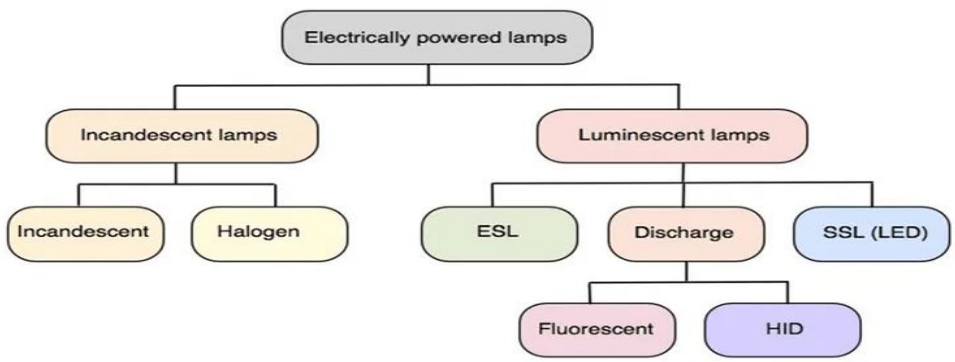
A lamp is an artificial source of light. Over the last 100 years, lamps have become an integral part of our daily lives.

Various types of lamps are available on the market. These lamps differ in their operating principle, materials used, and importantly – their energy efficiency.

The different types of lamps include:

- Incandescent Lamps
- Tungsten Halogen Lamps
- Fluorescent Lamps
- Compact Fluorescent Lamps
- Mercury Vapour Lamps
- Metal Halide Lamps
- High Pressure Sodium Vapour Lamps
- Low Pressure Sodium Vapour Lamps
- LED Lamps

The grouping of these various types of lamps has been illustrated in the diagram below:



A short comprehensive study of the photometric parameters (Luminous Efficacy, CRI, CCT, etc.) of the different lamps and their respective application areas are tabulated in comparison form below.

Lamp	Luminous Efficacy (lumens/ watt)	CCT (K)	CRI	Burning Hours (hours)	Applications
Incandescent	8-20	2800	100	1000	Indoor lighting specially domestic and also as decorative lighting
Halogen	20-25	2800	100	1200-1500	Flood lighting applications and theatre lighting
Fluorescent	50-70	2700; 4500; 6500	60-90	6000-10000	Indoor lighting specially domestic and small commercial applications
CFL	60-80	2700; 4500; 6500	60-90	6000-15000	Indoor lighting specially domestic and small commercial applications
Mercury Vapour	35-65	2500-4000	>80	20000-24000	At present used vary rarely in outdoor lighting applications
Metal-Halide	75-100	>6500	80-90	6000-15000	Used in wide area overhead lighting of commercial, industrial, and public spaces, such as parking lots, sports arenas, factories, and retail stores, as well as residential security lighting and automotive lighting
HPSV	100-150	<3000	65-85	10000-15000	Street Lighting applications, where good colour rendering is required
LPSV	150-200	<2000	negative	18000	Mostly used in Street Lighting applications where safety is priority and not the colour of the object. Mostly used during foggy weathers
LED	30-80; But nowadays as high as 200	2700; 4500; 6500	60-90	50000	LEDs were used as indicators and signals in earlier days but, now LEDs are used in almost all lighting applications ranging from indoor to road lighting to flood lighting.

APPENDIX I

CONTENT BEYOND THE SYLLABUS

APPENDIX I

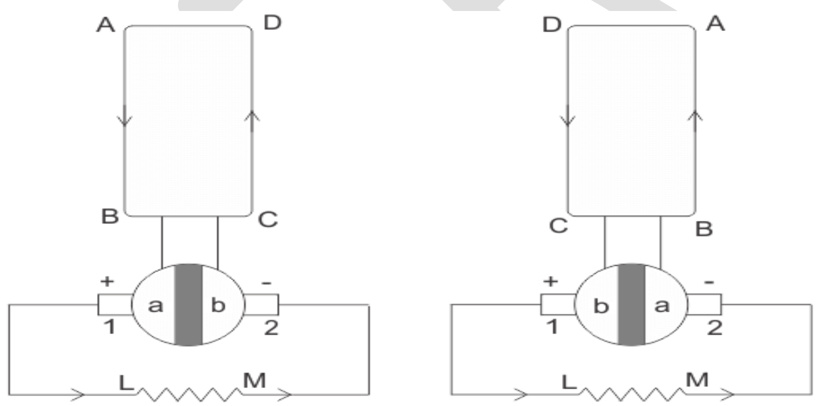
CONTENT BEYOND THE SYLLABUS

DC GENERATORS

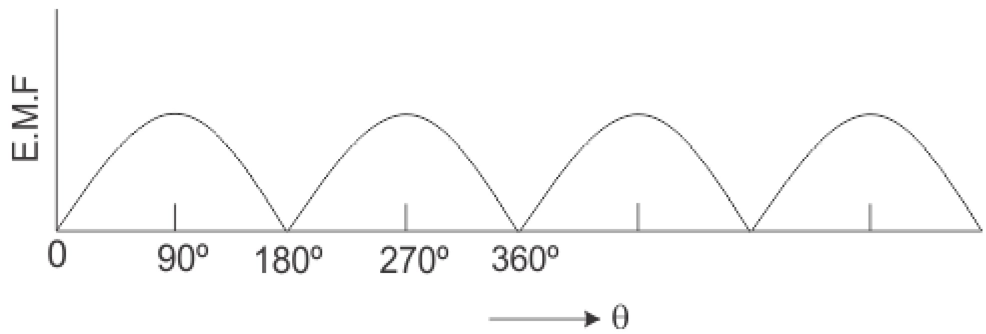
What is a DC Generator?

A DC generator is an electrical machine whose main function is to convert mechanical energy into electricity. When conductor slashes magnetic flux, an emf will be generated based on the electromagnetic induction principle of Faraday's Laws. This electromotive force can cause a flow of current when the conductor circuit is closed.

Working Principle of DC Generator



We can see that in the first half of the revolution current always flows along ABLMCD, i.e., brush no 1 in contact with segment a. In the next half revolution, in the figure, the direction of the induced current in the coil is reversed. But at the same time the position of the segments a and b are also reversed which results that brush no 1 comes in touch with the segment b. Hence, the current in the load resistance again flows from L to M. The waveform of the current through the load circuit is as shown in the figure. This current is unidirectional.



The above content is the basic **working principle of DC generator**, explained by single loop generator model. The positions of the brushes of DC generator are so that the change over of the segments a and b from one brush to other takes place when the plane of rotating coil is at a right angle to the plane of the lines of force. It is to become in that position, the induced EMF in the coil is zero.

EMF EQUATION OF A DC GENERATOR/MOTOR

As the armature rotates, a voltage is generated in its coils. In the case of a generator, the emf of rotation is called the Generated emf or Armature emf and is denoted as Er = Eg. In the case of a motor, the emf of rotation is known as Back emf or Counter emf and represented as Er = Eb.

The expression for emf is same for both the operations, i.e., for Generator as well as for Motor.

Derivation of EMF Equation of a DC Machine – Generator and Motor

Let,

- **P** – number of poles of the machine
- **ϕ** – Flux per pole in Weber.
- **Z** – Total number of armature conductors.
- **N** – Speed of armature in revolution per minute (r.p.m).
- **A** – number of parallel paths in the armature winding.

In one revolution of the armature, the flux cut by one conductor is given as:

$$\text{Flux cut by one conductor} = P\varphi \quad \text{wb} \ldots \ldots (1)$$

Time taken to complete one revolution is given as:

$$t = \frac{60}{N} \quad \text{seconds} \quad \ldots\ldots..(2)$$

Therefore, the average induced e.m.f in one conductor will be:

$$e = \frac{P\varphi}{t} \quad \ldots\ldots..(3)$$

Putting the value of (t) from Equation (2) in the equation (3) we will get

$$e = \frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts} \quad \ldots\ldots..(4)$$

The number of conductors connected in series in each parallel path = Z/A.

Therefore, the average induced e.m.f across each parallel path or the armature terminals is given by the equation shown below:

$$E = \frac{P\varphi N}{60} \times \frac{Z}{A} = \frac{PZ\varphi N}{60\ A} \quad \text{volts} \quad \text{or}$$

$$E = \frac{PZ\varphi n}{A} \quad \ldots\ldots.(5)$$

Where n is the speed in revolution per second (r.p.s) and given as:

$$n = \frac{N}{60}$$

For a given machine, the number of poles and the number of conductors per parallel path (Z/A) are constant. Hence, equation (5) can be written as:

$$E = K\varphi n$$

Where K is a constant and given as:

$$K = \frac{PZ}{A}$$

Therefore, the average induced emf equation can also be written as:

$$E \propto \varphi n \quad \text{or}$$

$$E = K_1 \varphi N$$

Where K_1 is another constant and hence induced emf equation can be written as:

$$E \propto \varphi N \quad \text{or}$$

$$E \propto \varphi \omega$$

Where ω is the angular velocity in radians/second is represented as:

$$\omega = \frac{2\pi N}{60}$$

Thus, it is clear that the induced emf is directly proportional to the speed and flux per pole. The polarity of induced emf depends upon the direction of the magnetic field and the direction of rotation. If either of the two is reversed the polarity changes, but if two are reversed the polarity remains unchanged.

This induced emf is a fundamental phenomenon for all the DC Machines whether they are working as a generator or motor.

If the DC Machine is working as a Generator, the induced emf is given by the equation shown below:

$$E_g = \frac{PZ\varphi N}{60\,A} \quad \text{volts}$$

Where $\mathbf{E_g}$ is the **Generated Emf**

If the DC Machine is working as a Motor, the induced emf is given by the equation shown below:

$$E_b = \frac{PZ\varphi N}{60\,A} \quad \text{volts}$$

In a motor, the induced emf is called **Back Emf ($\mathbf{E_b}$)** because it acts opposite to the supply voltage.

Induced emf of DC generator is

$$e = \phi P \frac{N}{60} X \frac{Z}{A}\, volts$$

For Simple wave wound generator

Numbers of parallel paths are only 2 = A

Therefore,

Induced emf for wave type of winding generator

$$\frac{\phi PN}{60} X \frac{Z}{2} = \frac{\phi ZPN}{120}\, volts$$

For Simple lap-wound generator

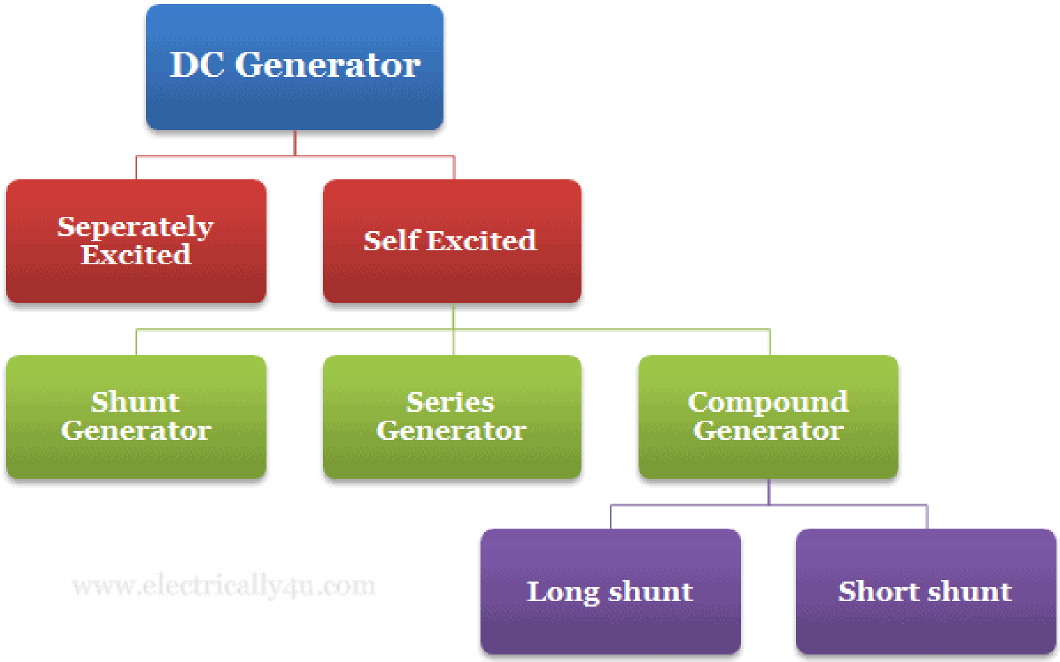
Here, number of parallel paths is equal to number of conductors in one path i.e. P = A

Therefore,
Induced emf for lap-wound generator is

$$E_g = \frac{\phi ZN}{60} X \frac{P}{A}\, volt$$

TYPES OF DC GENERATOR AND ITS EQUATION

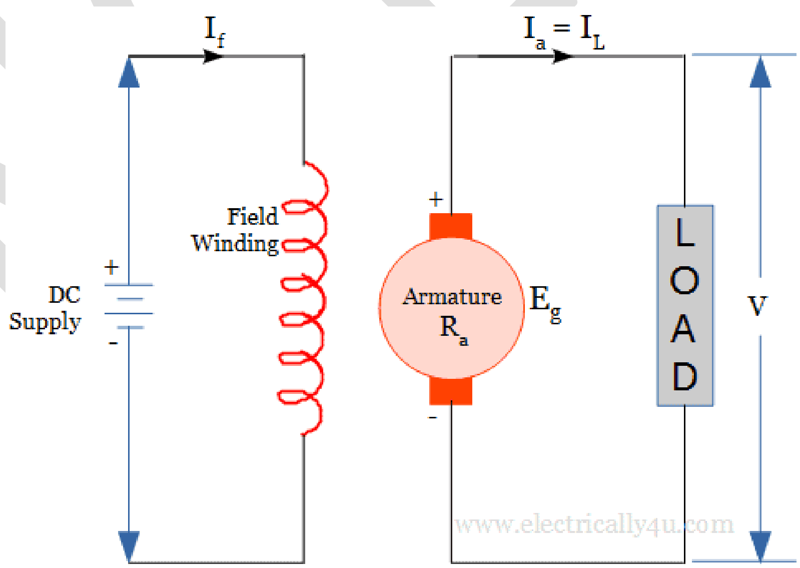
DC generators are classified based on the way in which the field windings are excited. The different types of DC generator are shown below



Before getting into the topic, learn the construction of DC Generator and its working principle.

Separately excited DC Generator

It is a type of DC generator, in which the field windings are excited from a separate source of supply. The following figure shows the circuit diagram of a separately excite dc generator.



In the above circuit diagram,

I_f – Field current, I_a – Armature current, I_L – Load current,

R_a – Armature winding resistance, V – terminal voltage

Let V_{br} be the voltage drop at the brush contacts.

Armature current is given by, $I_a = I_L$

Applying Kirchoff's Voltage Law to the armature circuit, $E_g – I_a R_a – V – V_{br} = 0$

Thus, the generated Emf equation $E_g = I_a R_a + V + V_{br}$

Power developed in the DC generator = $E_g I_a$

Power delivered to the load = $V I_a$

Self- Excited DC Generator

The self-excited generator produces DC output, whose field windings are excited by the current produced by the generator itself. No separate source is used for filed excitation.

In this type of generators, some flux is already present in the poles due to residual magnetism. When the armature is rotated with the residual flux, a small emf and hence some current is induced in the armature conductors. This current will produce more flux, which in turn produces more current to flow through the field winding. It will continue until the field current reaches its rated value.

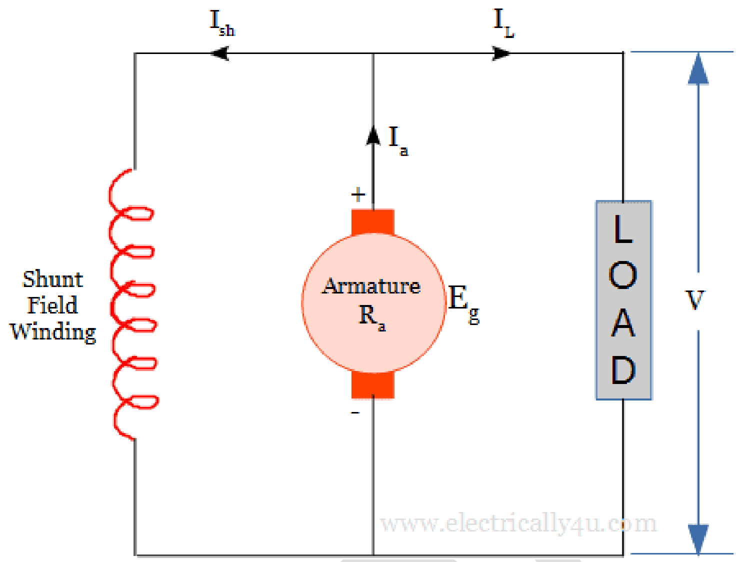
There are three types of self-excited DC generator based on the way, in which the field coils and armature are connected. They are

1. Shunt-wound Generator
2. Series wound Generator
3. Compound wound Generator

DC Shunt Generator

In DC shunt type generator, the field windings are connected across or in parallel with the armature conductors. The field winding has more number of turns and thin wire, having high resistance.

The load is connected across the armature as shown in the diagram below. A small amount of current will flow through the field winding and more current flows through the armature.



In the above circuit diagram,

I_{sh} – Shunt field current, I_a – Armature current, I_L – Load current,

R_a – Armature winding resistance, V – terminal voltage, V_{br} – Brush contact drop

Armature current is given by, $I_a = I_L + I_{sh}$

Shunt field current $I_{sh} = V/R_{sh}$, Where R_{sh} – shunt field resistance

Terminal voltage equation is given by, $V = E_g – I_a R_a – V_{br}$

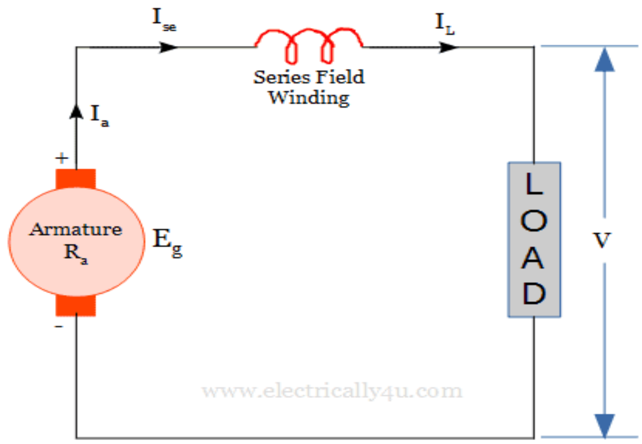
Power developed in the DC generator = $E_g I_a$

Power delivered to the load = $V I_L$

DC Series Generator

As the name says, the field winding is connected in series with the armature conductors. Such generators are called a DC series Generator. They have less number of turns with a thick wire having low resistance.

Here, the load is connected in series with the field winding and armature conductors. So all the current flows through field winding and load.



In the above circuit diagram,

I_{se} – Shunt field current, I_a – Armature current, I_L – Load current,

R_a – Armature winding resistance, V – terminal voltage, V_{br} – Brush contact drop

Armature current is given by, $I_a = I_{se} = I_L$

Terminal voltage equation is given by, $V = E_g – I_a R_a – I_a R_{se} – V_{br}$

Power developed in the DC generator = $E_g I_a$

Power delivered to the load = $V I_L$

DC Compound Generator

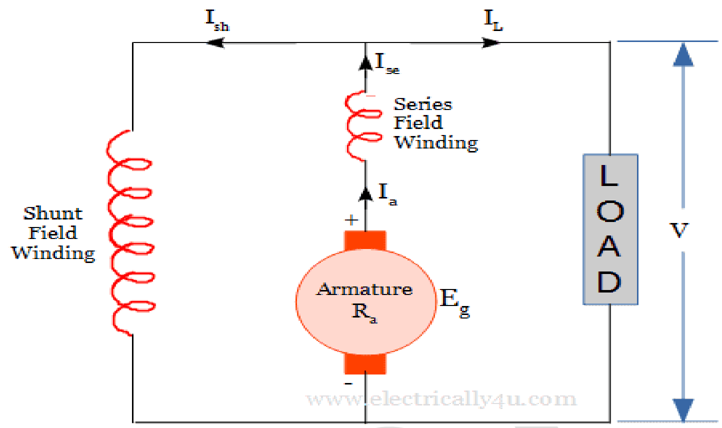
DC compound generator has both shunt field winding and series field winding. One field winding is connected in series with the armature and another field winding is connected in parallel with the armature.

DC Compound generator can be classified into two different types based on the way of connection

1. Long shunt DC Compound generator
2. Short shunt DC Compound generator.

Long shunt DC Compound generator

The below figure shows the circuit diagram of long shunt DC compound generator. In this, shunt field winding is connected in parallel with a combination of series field winding and armature conductors.



In the above circuit diagram,

I_{sh} – Shunt field current, I_{se} – Shunt field current, I_a – Armature current, I_L – Load current,

R_a – Armature winding resistance, V – terminal voltage, V_{br} – Brush contact drop

Armature current is given by, $I_a = I_{se} = I_L + I_{sh}$

Shunt field current $I_{sh} = V/R_{sh}$, Where R_{sh} – shunt field resistance

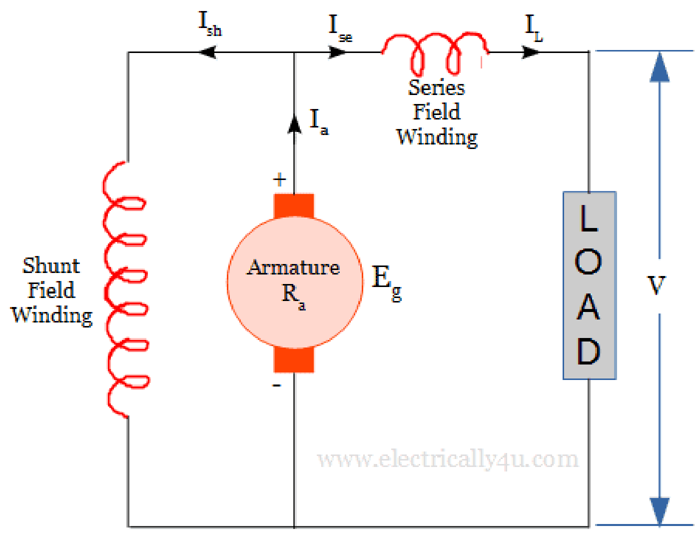
Terminal voltage equation is given by, $V = E_g - I_a R_a - I_a R_{se} - V_{br}$

Power developed in the DC generator = $E_g I_a$

Power delivered to the load = $V I_L$

Short shunt DC Compound generator

In short shunt DC compound generator, the shunt field winding is connected across the armature conductors and this combination is connected in series with a series field winding. The following figure shows the circuit diagram of short shunt DC compound generator.



In the above circuit diagram,

I_{sh} – Shunt field current, I_{se} – Shunt field current, I_a – Armature current, I_L – Load current,

R_a – Armature winding resistance, V – terminal voltage, V_{br} – Brush contact drop