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 209 ELECTRICAL TECHNOLOGY

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	Develop the basic knowledge in fundamentals of various circuit analysis techniques.
CO 2	Apply the various theorems in circuit analysis and its applications.
CO 3	Develop the knowledge about ac circuits and three phase RLC networks.
CO 4	Explain the construction, working and characteristics of DC machines in electrical engineering
CO 5	Explain the construction, working and characteristics of Induction machines and transformers in electrical engineering
CO 6	Develop the basic knowledge about various special electrical machines and their real time applications with case studies

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	2	-	2	-	-	-	-	-	-	-	2	2	2
CO 2	3	2	-	2	-	-	-	-	-	-	-	2	2	2
CO 3	3	2	-	2	-	-	-	-	-	-	-	2	1	2
CO 4	3	2	-	2	-	-	-	-	-	-	-	2	1	2
CO 5	3	2	3	2	-	-	-	-	-	-	-	2	1	2
CO 6	3	2	-	2	-	-	-	-	-	-	-	2	3	2

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

SYLLABUS

Course code	Course Name	L-T-P - Credits	Year of Introduction
EE209	Electrical Technology	3-1-0 -4	2016

Prerequisite : Nil

Course Objectives

- To understand about the network Elements, types of networks & analysis of complex circuits using Mesh current & Nodal voltage method.
- To impart knowledge on the solution methods of AC and DC circuits.
- To understand the working principle and characteristics of all electrical machines

Syllabus

Types of Networks- mesh current & Nodal voltage method for DC and AC circuits-Basics of Circuit theorems-AC circuits- RLC circuits- series and parallel resonance-Three phase circuits- Power measurements in three phase circuits-DC machines construction – working- EMF equation – Characteristics of DC shunt and series motor and generator-Starters- Concept of transformers-EMF equation- concept of rotating magnetic field- working principle of induction motors-special machines and their application.

Expected outcome.

i. Understand the circuit analysis and theorems.
ii. Understand the concept of three phase RLC circuits.
iii. Get knowledge in construction and working of dc machines
iv. Get knowledge in special machines and their applications.
v. Understand the construction and working of induction machines.

Text Book:

1. Theraja B.L., Theraja A.K. *A Text Book of Electrical Technology*, Vol.II "AC & DC Machines", publication division of Nirja construction & development (p) Ltd., New Delhi, 1994.

2. Sudhakar, A. and Shyam Mojan, S.P. *Circuits and Networks Analysis and Synthesis*, Tata McGraw Hill Publishing Co. Ltd, New Delhi, 1994.

References:

1. Raina K.B., Bhattacharya S.K. *Electrical Design Estimating & Costing*, New Age International P Ltd.,2001.

2. Muthusubramanian R & Ayyappan K, *Circuit Theory*, Anuradha Publishign Pvt Ltd., Tamil Nadu 1999.

3. Arumugam & Premkumar, *Electric Circuit Theory*, Khanna Publishers. 2002

Course Plan

Module	Contents	Hours	Sem. Exam Marks
I	**BASICS OF CIRCUIT ANALYSIS** Types of Networks – Sources transformation – Star – Delta transformation – formation of matrix equation and analysis of circuits using mesh current & Nodal voltage method for DC and AC circuits.	10	15%
II	**BASICS OF CIRCUIT THEOREMS** Thevenin's theorem – Norton's theorem – superposition theorem – maximum power transfer theorem – statement, illustration & application to DC circuits.	9	15%

FIRST INTERNAL EXAMINATION			
III	**AC CIRCUITS:** Review of Basic concepts – solution of RLC circuit – power – power factor and energy relation – series resonance – parallel resonance – Q factor – bandwidth. Three phase star-delta connections – characteristic equations – phasor diagrams – solution of 3-phase balanced circuits & unbalanced circuits – Three phase power measurement suing watt meters	10	15%
IV	**DC MACHINES:** Review of constructional details – Working principle of DC generator – EMF equation – No load & load characteristics of shunt generator – working principle of DC motor – back emf – equations for torque & power – characteristics of shunt, series & compound motors – Necessity of starters and their types— power stages – efficiency.	9	15%
SECOND INTERNAL EXAMINATION			
V	**TRANSFORMERS** Construction – working principle – emf equation & voltage regulation – vector diagram **3-PHASE INDUCTION MOTORS** Production of rotating magnetic field – torque equation, torque slip characteristics power stages and efficiency simple problems – starters & methods of speed control (quantitative treatment only).	10	20%
VI	**SPECIAL MACHINES / APPLICATIONS** (Qualitative treatment only) Working principle of single phase induction motor – capacitor start & capacitor run motors – Universal motor – stepper motor – servomotor - Synchronous motor Selection of motors with justifications for the following services, *Machine tools *Washing machine *Cranes *WetGrinder *Steel mills * Mixie *Hoist *Electric traction	9	20%
END SEMESTER EXAM			

QUESTION PAPER PATTERN

Maximum Marks : 100 Exam Duration:3 hours

PART A: FIVE MARK QUESTIONS

8 compulsory questions –1 question each from first four modules and 2 questions each from last two modules (8 x 5= 40 marks)

PART B: 10 MARK QUESTIONS

5 questions uniformly covering the first four modules. Each question can have maximum of three sub questions, if needed. Student has to answer any 3 questions

(3 x10 = 30 marks)

PART C: 15 MARK QUESTIONS

4 questions uniformly covering the last two modules. Each question can have maximum of four sub questions, if needed. Student has to answer any two questions

(2 x15 = 30 marks)

QUESTION BANK

Q:NO:	QUESTIONS	CO	KL
MODULE I			
1	Discuss the various types of electrical networks	CO1	K2
2	Compare network and circuit.	CO1	K4
3	Discuss in detail about the source transformation technique in electrical engineering.	CO1	K2
4	Derive the equation for Start –Delta and Delta-Star transformation equations.	CO1	K4
5	Solve Star- Delta transformation problems	CO1	K5
6	Define the step by step procedure for solving the mesh analysis.	CO1	K1
7	Define mesh matrix and Cramer's rule for solving mesh problems.	CO1	K1
8	lve mesh analysis problems.	CO1	K4
9	Define the step by step procedure for solving the Node analysis.	CO1	K1
10	ıte and define KCL and KVL and justify the importance of the KCL and KVL in network analysis.	CO1	K1
11	lve Node analysis problems.	CO1	K4
MODULE II			
1	Discuss in detail about the various network theorems in circuit analysis with the statement.	CO2	K2
2	State and prove the superposition theorem.	CO2	K1
3	Solve superposition theorem problems.	CO2	K4

4	State and prove Thevenin's theorem.	CO2	K1
5	Solve Thevenins theorem problems.	CO2	K4
6	State and prove Norton's theorem.	CO2	K1
7	Norton's theorem problems.	CO2	K4
8	Investigate the condition for maximum power transfer using suitable circuit theorems.	CO2	K6
9	State and prove maximum power transfer theorem	CO2	K1
10	Solve maximum power transfer theorem problems.	CO2	K4
MODULE III			
1	Compare AC and DC circuits.	CO3	K4
2	Discuss in detail about the analysis of pure R,L,C circuits.	CO3	K2
3	Discuss in detail about the analysis of RL,RC and RLC circuits.	CO3	K2
4	Solve RLC circuit problems.	CO3	K4
5	Discuss in detail about the series resonance circuit.	CO3	K2
6	Discuss in detail about the parallel resonance circuit.	CO3	K2
7	Compare series and parallel resonance circuit.	CO3	K4
8	Derive equation for resonance frequency in series resonance circuit.	CO3	K2
9	Define Bandwidth and Quality factor.	CO3	K1
10	Resonance circuit problems solving.	CO3	K4
11	Investigate the various types of AC powers.	CO3	K6
12	Discuss in detail about the analysis and generation of three phase power	CO3	K2
13	Compare Star and Delta connection for balanced three phase circuits with voltage and current relations.	CO3	K4

14	Three phase ac networks problem solving.	CO3	K4
15	Discuss in detail about the calculation of power in three phase systems using two wattmeter method.	CO3	K2
MODULE IV			
1	Derive EMF equation of DC Generator	CO4	K5
2	With neat sketch explain the construction of DC Machines	CO4	K3
3	Discuss in detail about the necessity of starters in DC motors.	CO4	K2
4	With neat sketch explain the working of 3 point starters	CO4	K3
5	Derive equation for back EMF in DC motors	CO4	K5
6	Discuss the various types of dc generators with neat diagram and write the voltage equation for all types.	CO4	K2
7	Derive equation for torque of a dc motor	CO4	K5
8	plain different types of DC Motors according to the excitation method.	CO4	K2
9	Explain about the back emf as regulating mechanism in DC Motors	CO4	K2
10	th neat sketch explain the power flow diagram of a generator.	CO4	K4
11	plain back EMF and write the Back EMF equation for DC Motors.	CO4	K2
12	th neat sketch explain the power flow diagram of a motor.	CO4	K2
13	Investigate the load and open circuit characteristics of DC generators	CO4	K5
14	Investigate working principle of DC motors.	CO4	K5
MODULE V			

1	Define slip and justify at which time the slip should be maximum in 3 phase induction motors	CO5	K2
2	Elucidate in detail about the construction and types of single phase transformers	CO5	K4
3	Discuss the various methods of starting squirrel cage induction motors	CO5	K2
4	Derive EMF equation of the transformers	CO5	K5
5	Investigate the construction of three phase induction motors and classify its types.	CO5	K5
6	Elucidate in detail about short circuit and open circuit test of transformers	CO5	K3
7	Investigate the torque slip characteristics of 3 phase induction motors	CO5	K5
8	Compare squirrel cage and slip ring induction motor	CO5	K4
9	Discuss in detail about the basic working principle of three phase induction motors.	CO5	K2
10	Narrate the properties of ideal transformer. Sketch its phasor diagram	CO5	K3
11	Briefly explain the losses in a transformer.	CO5	K2
12	Explain in detail with necessary sketch the construction, working principle, emf equation, transformation ratio, and losses in a transformer.	CO5	K2
13	Explain any four starting methods of three phase induction motors.	CO5	K2
MODULE VI			
1	Discuss the types of single phase induction motors	CO6	K3
2	Discuss the basic working principle behind the single phase induction motors	CO6	K3
3	With neat sketch discuss about the capacitive start and	CO6	K2

	capacitive runt type induction motors		
4	Discuss in detail about double revolving field theory	CO6	K3
5	Investigate the concept of double revolving field theory and its application in the working of single phase induction motors.	CO6	K5
6	Discuss the various starting methods of single phase induction motors	CO6	K3
7	Why a single phase induction motor is not self-starting? How it can be made self-starting	CO6	K2
8	Compare capacitive start and capacitive run induction motors and mention its applications.	CO6	K5
9	Investigate the basic working principle behind the single phase induction motors	CO6	K5
10	Briefly explain different types of rotors of an alternator.	CO6	K2
11	Derive emf equation of an alternator.	CO6	K5
12	Explain the emf method to find the voltage regulation of an alternator.	CO6	K2
13	Numerate the steps with necessary equation for finding voltage regulation of alternator using synchronous impedance method.	CO6	K1

APPENDIX 1

CONTENT BEYOND THE SYLLABUS

S:NO;	TOPIC	PAGE NO:
1	ALTERNATORS	252

MODULE I

BASICS OF CIRCUIT ANALYSIS

INTRODUCTION

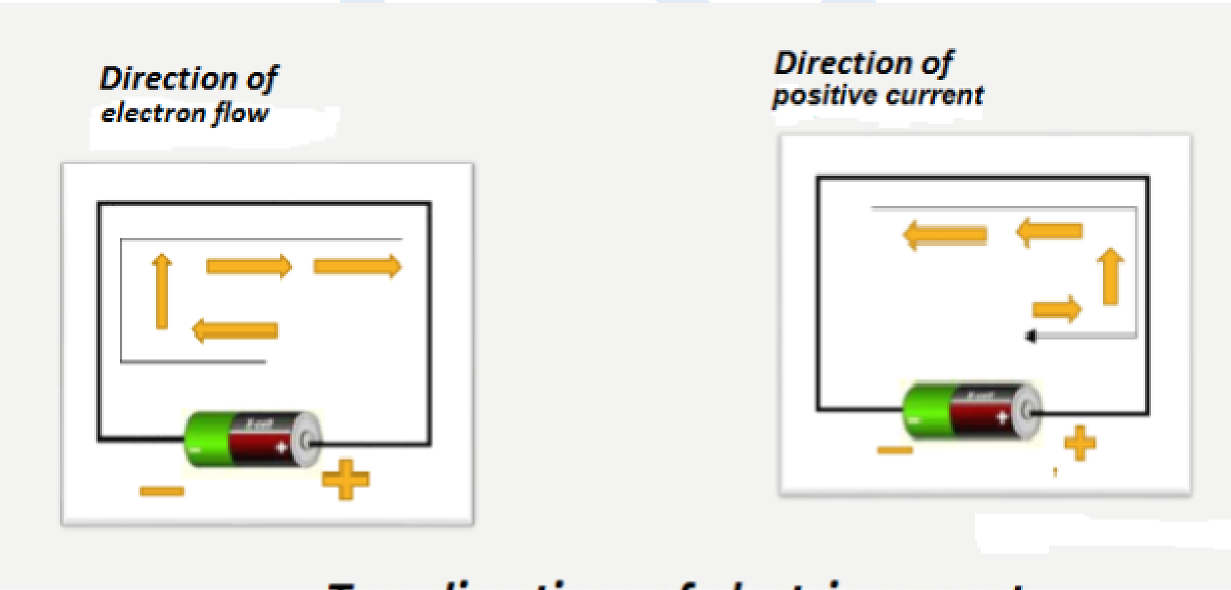
Understanding of electrical terms is compulsory for engineers. As you study electricity in your engineering program, and as you work with electricity in the power plants, industrial plants, you will hear, read, and use various electrical terms. These terms have very exact meanings. You must know what 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.

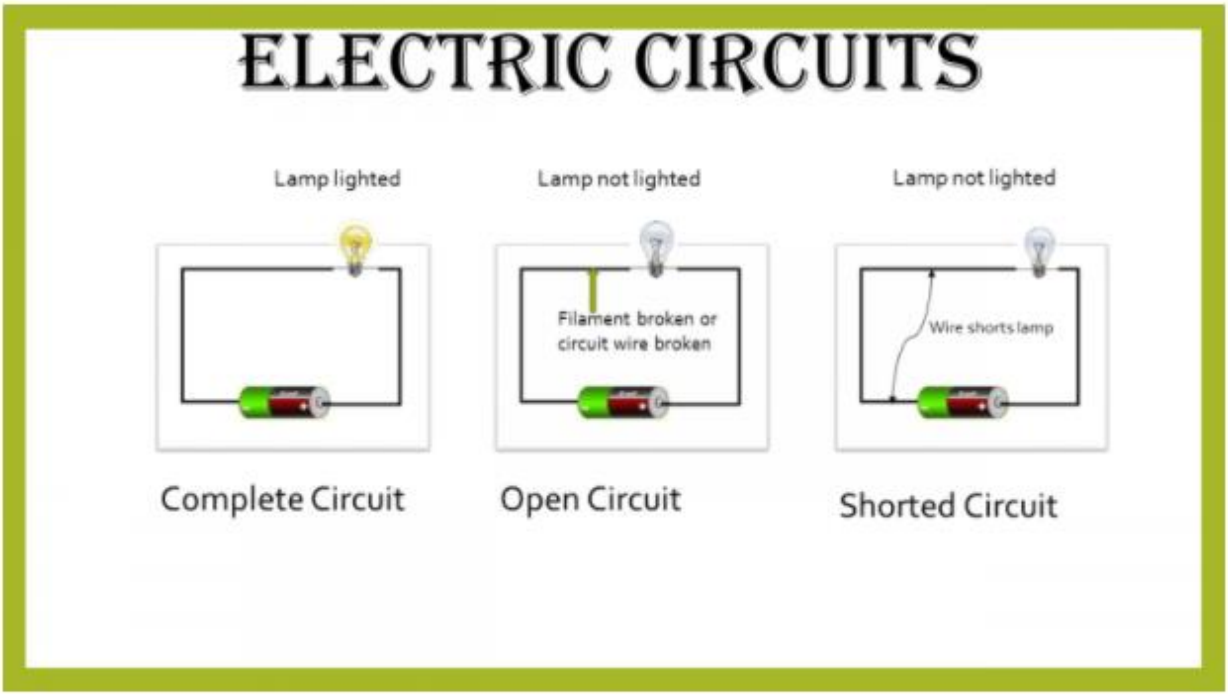


Two directions of electric current

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.

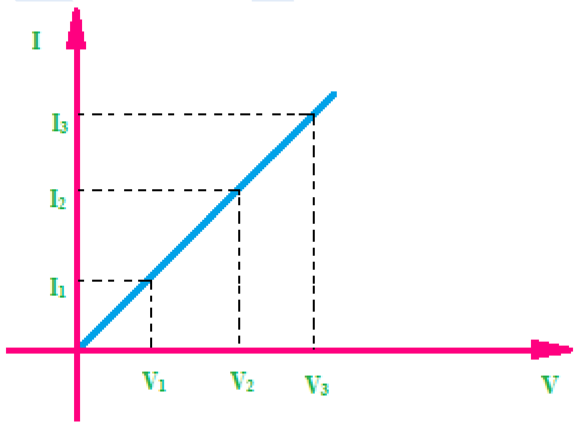
Basic Properties of Electric Circuits

- 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.

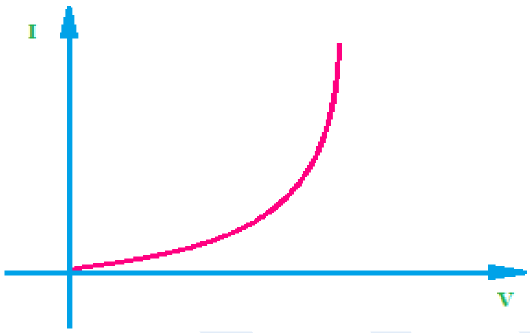
So we can also say if the parameters of an electrical circuit are constant, they do not change with the change of voltage and current then that circuit **is called linear circuit**. Actually, most of the cases the property of an electrical circuit depends on the property of connected elements.



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

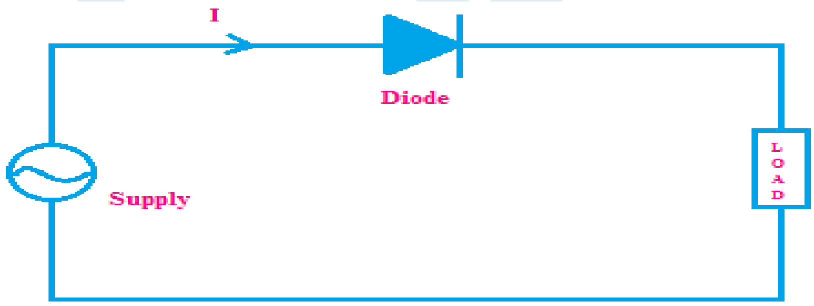
2. Non-linear Circuit: When the flow of current through an electrical circuit changes ununiformly with the changes of voltage then the circuit **is called Non-linear Circuit**.

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



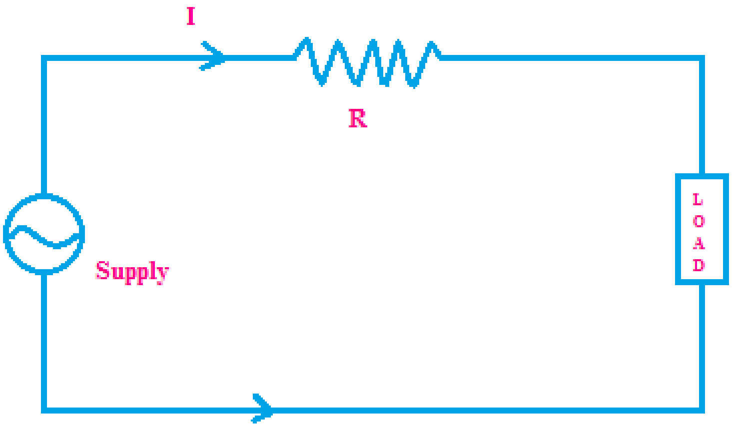
3. Unilateral Circuit: When an electrical circuit changes its properties with the change of the direction of the flow of current then the circuit **is called Unilateral circuit**.

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:

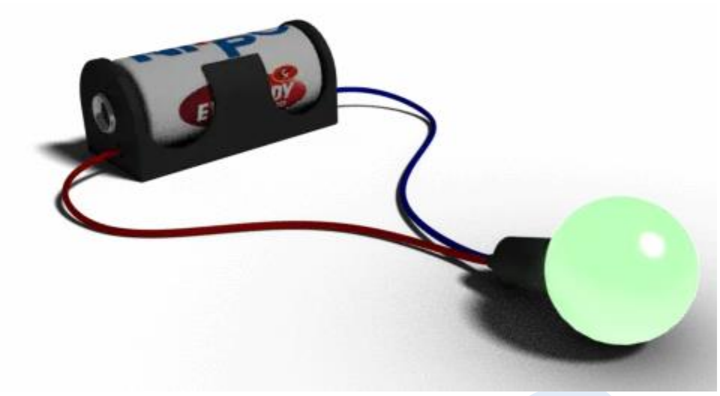
A circuit which contains no energy source is called **passive network**. The passive network contains resistor, capacitor and inductor.

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**.

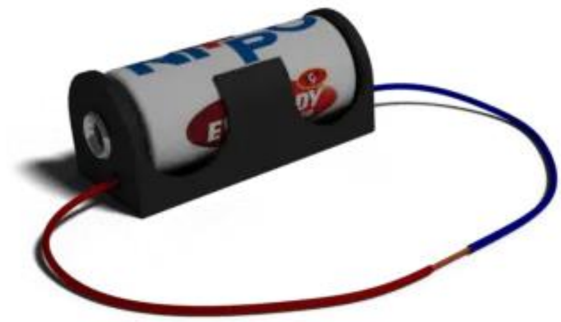
8. Closed Circuit

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**.

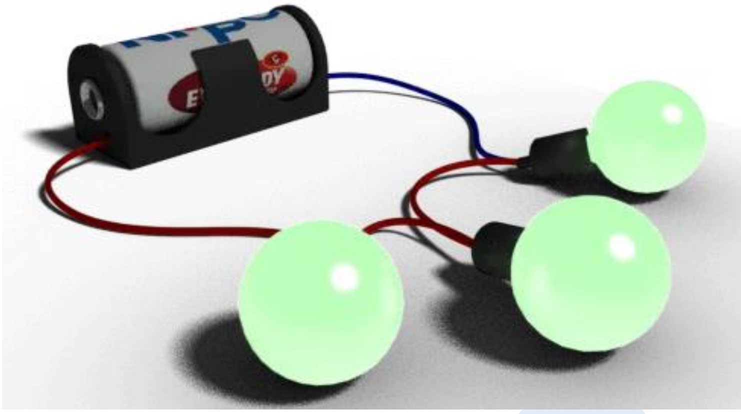


Electric circuits can be further categorized according to their structural features into either:

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

Series Circuit

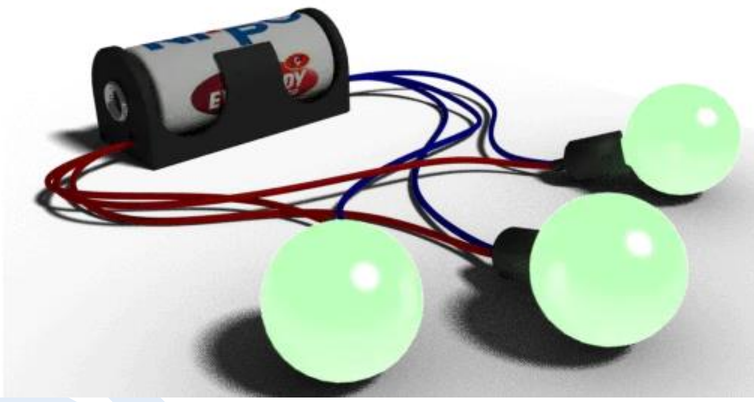
When all elements of a circuit are connected one after another in tail to head fashion and due to which there will be only one path of flowing current then the circuit is called **series circuit**. The circuit elements then are said to be series connected. In the series electrical circuit, same current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



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:

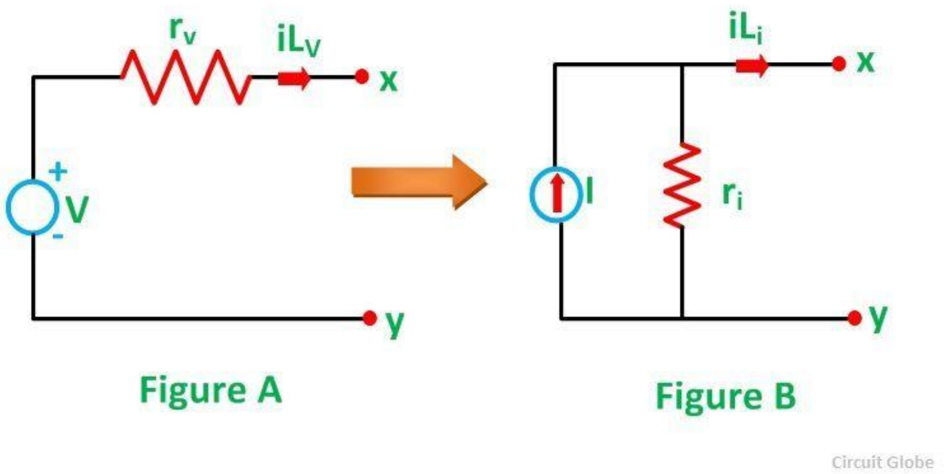


Figure A represents a practical voltage source in series with the internal resistance r_v, while figure B represents a practical current source with parallel internal resistance r_i

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:

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

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.

$V = I \times r_i$

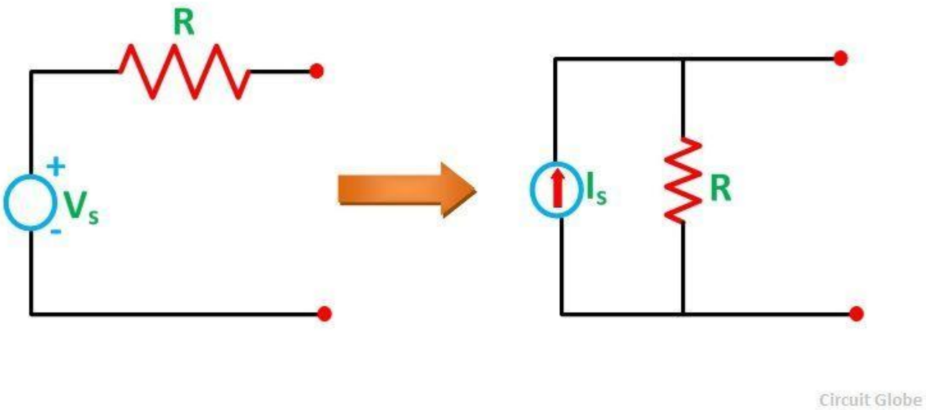
Therefore, we will get,

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

$$r_v = r_L$$

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.

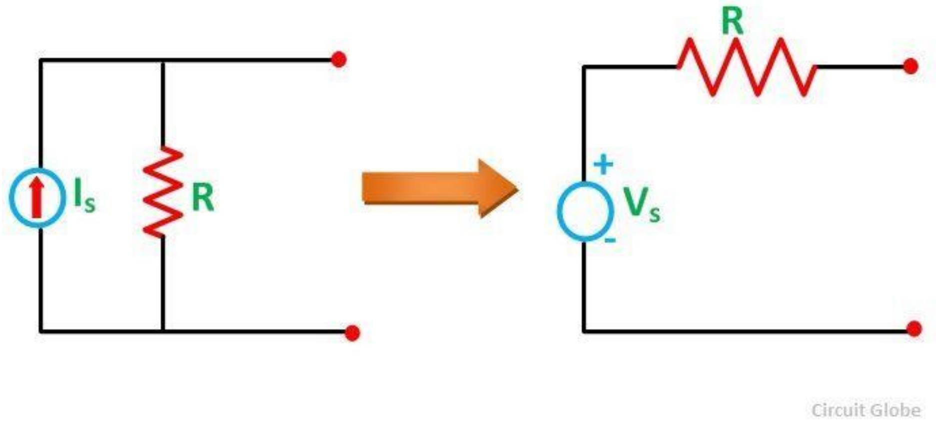
Source Transformation: Conversion of Voltage Source into Current Source



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:

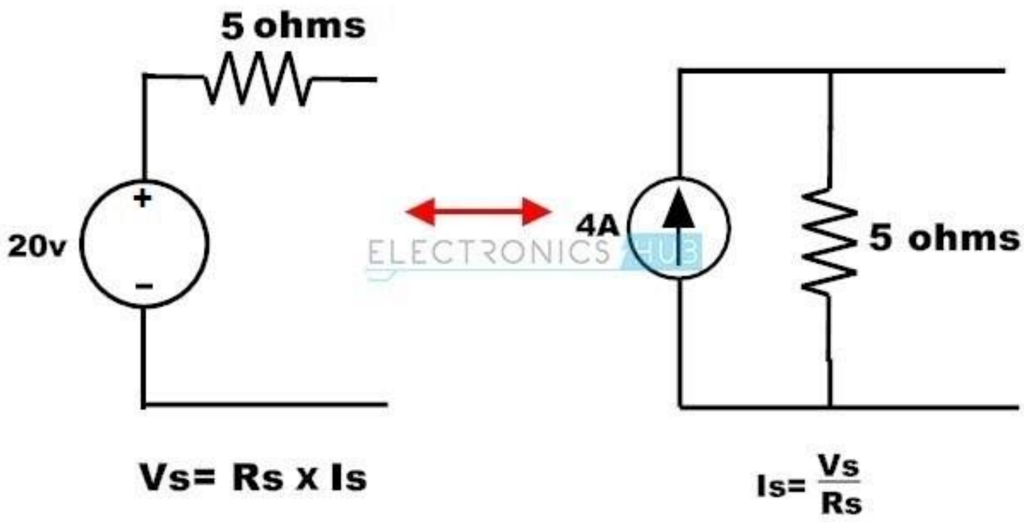
Consider the below voltage source circuit with a voltage of 20 V and a internal resistance of 5 ohms. This circuit is transformed into the current source by placing a resistor of the same value with a current source. This current source value can be determined by,

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:

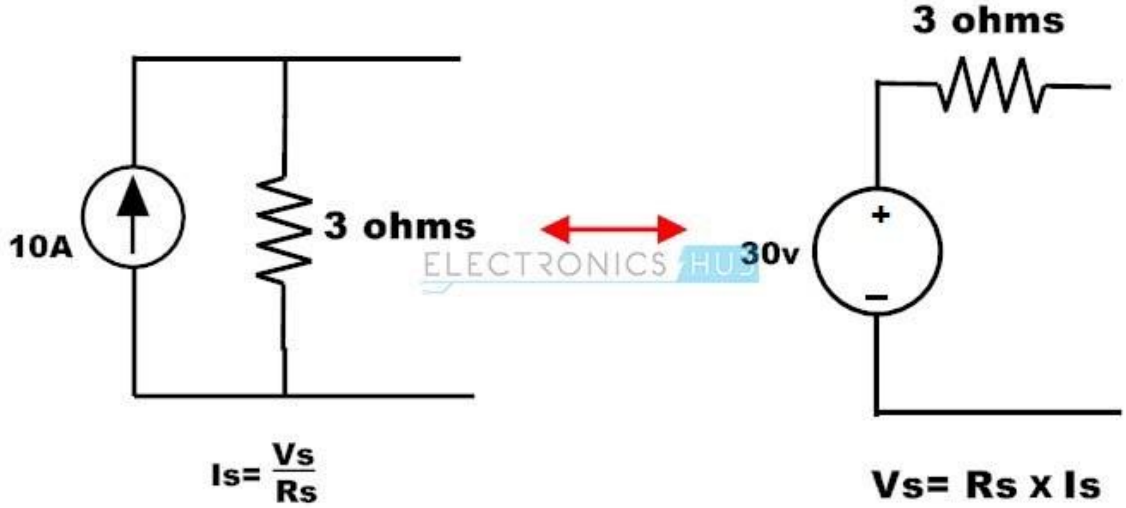
Consider the below example for current source transformation, where current source is of 10A with a parallel resistance of 3 ohms. To calculate the value of voltage in voltage source apply the simple ohms law, then,

Vs = Is * Rs

Vs = 10 * 3

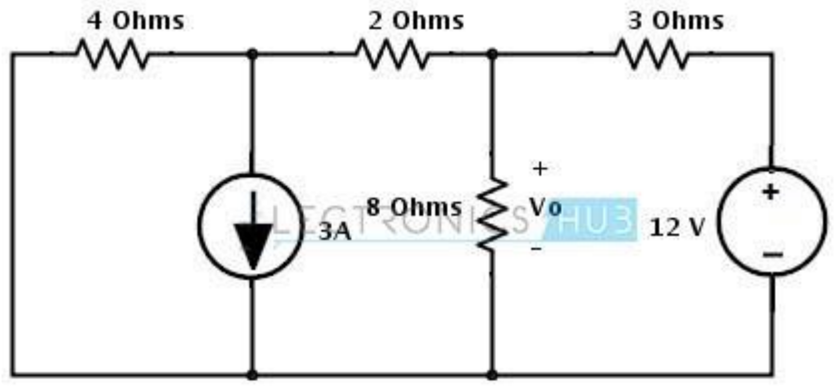
= 30 Volts.

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

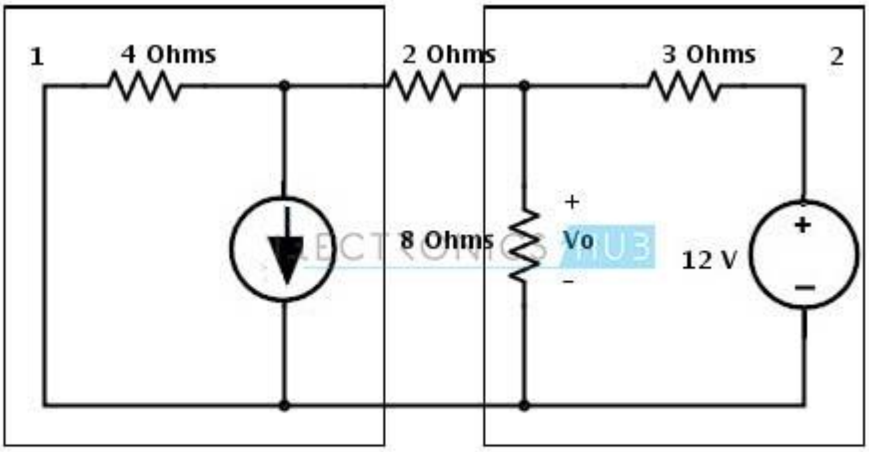


Example 3:

- 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.



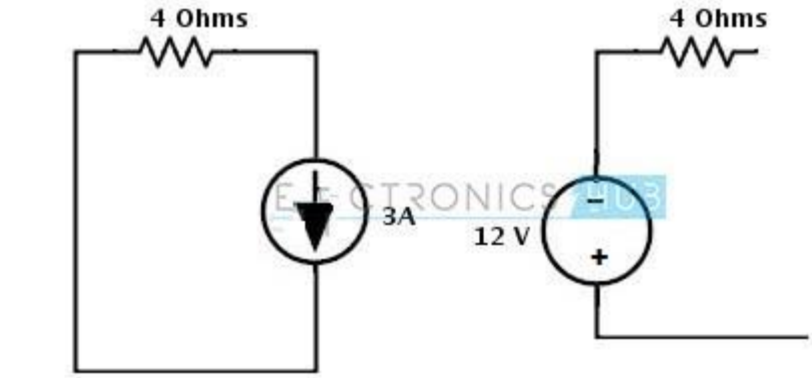
- First, consider the current source with a parallel resistance of 4 ohms. This current source can be transformed into a voltage source by 4 ohms series with a voltage source and voltage source value is determined as

Vs = Is * R

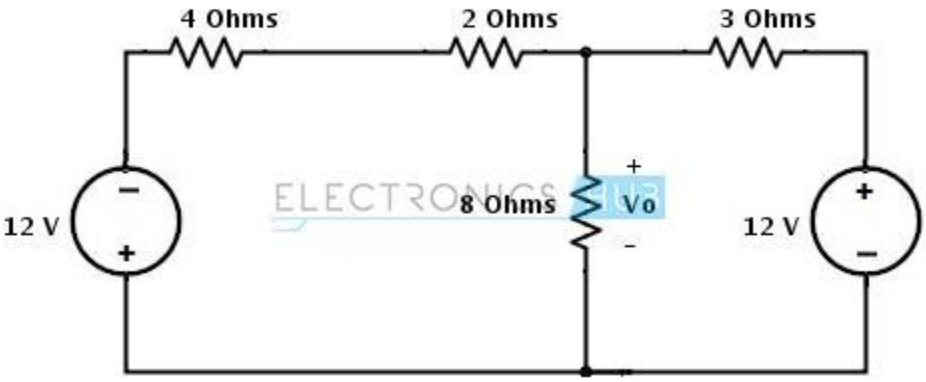
= 3* 4

= 12 Volts

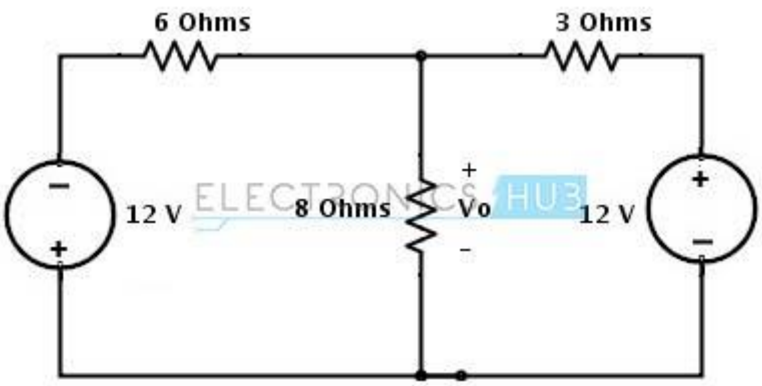
Consider the direction of the current as it downwards so the voltage terminals in voltage source are also changes as shown in figure.



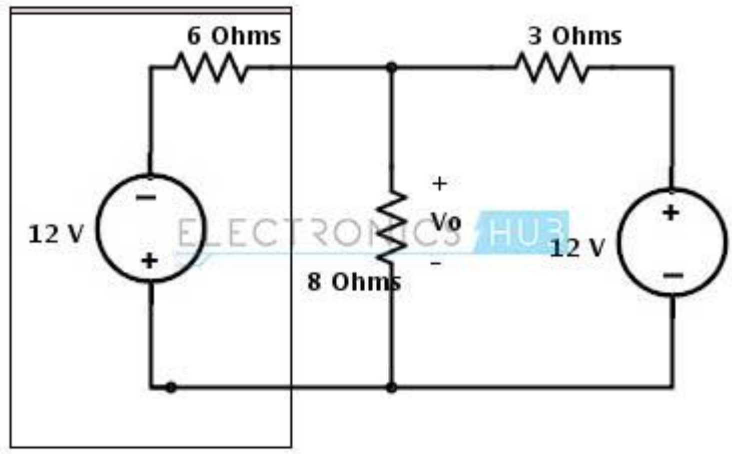
- Place the above voltage source with a series resistance in the circuit, then we get below figure.



- 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.



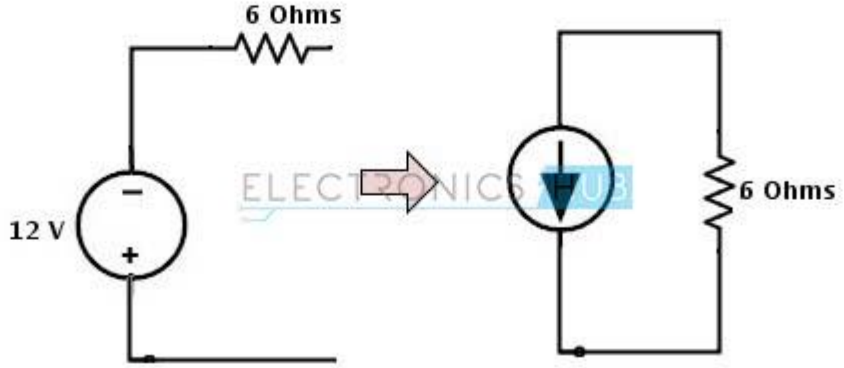
- This 12V voltage source with 6 ohm resistor combination can be converted into the current source by placing 6 ohms resistor in parallel with a current source. And the value of current in current source can be determined as

Is = Vs/R

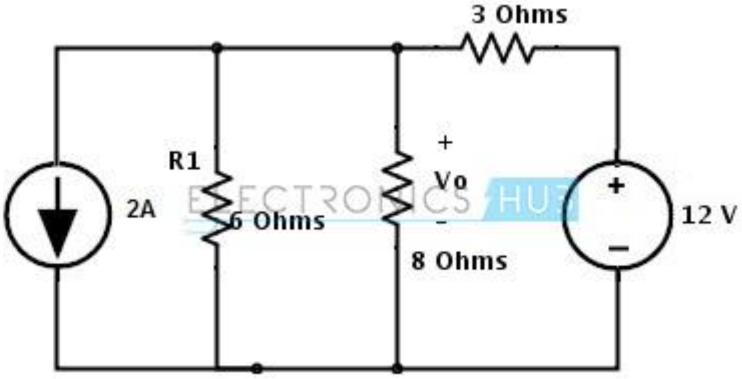
= 12/6

= 2Amps

The direction of current flow is represented in below figure.



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



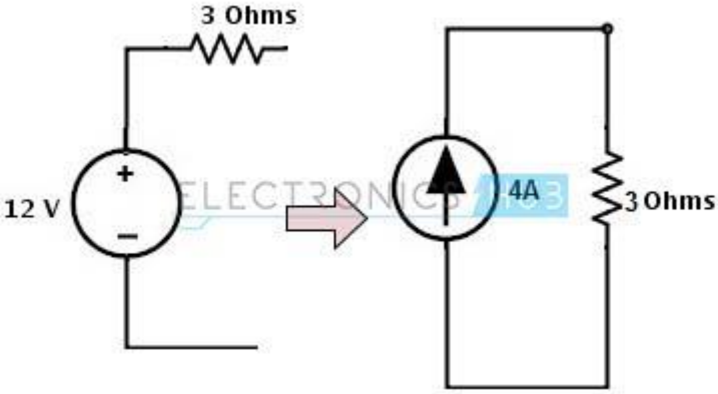
- On the right hand side, there is a voltage source with a 3 ohms resistor so this can be transformed into a current source by placing a 3 ohm resistor in parallel with a current source and this current source value is calculated as

Is = Vs/Rs

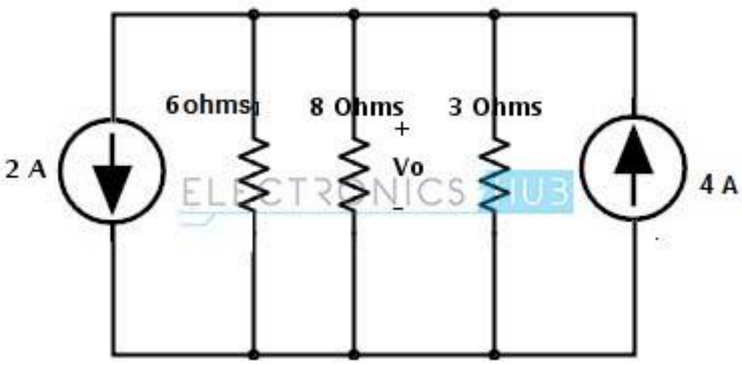
= 12/ 3

= 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

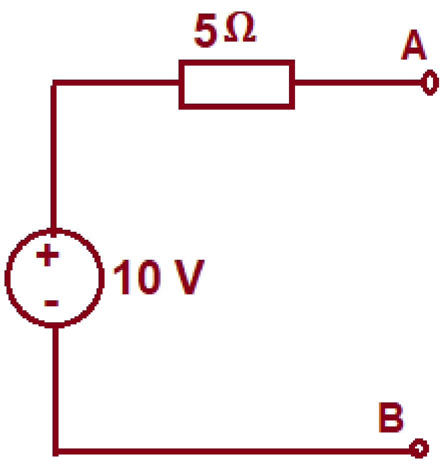
Vo = Io * Ro

= 0.4 * 8

= 3.2 Volts

Example 4:

Obtain an equivalent current source for the given voltage source:



Solution:

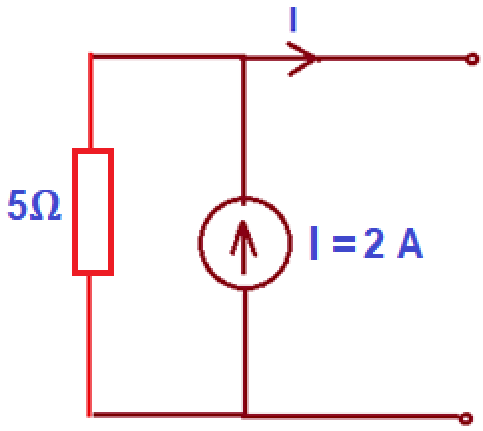
Let us first short terminals A & B and then find the current through the circuit. The current I through the circuit will be given as below.

I = V/R

= 10/5

= 2 A

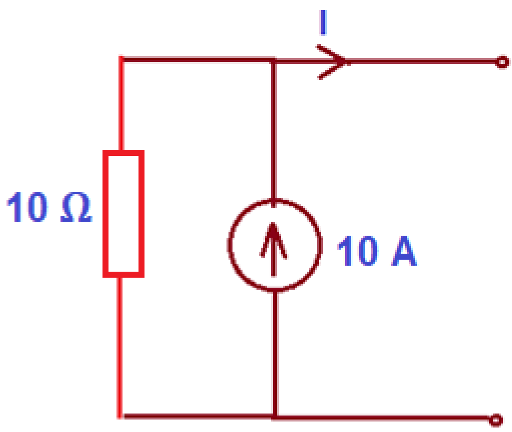
This means, the equivalent current source should be capable of supplying 2 A of current. Hence strength of source will be 2 A. Again, the internal impedance / resistance of voltage source is 5 Ω, this resistance should be connected in parallel with the current source. Therefore, the equivalent current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



Equivalent Current Source

Example 5:

Convert the following current source to equivalent voltage source.



Solution:

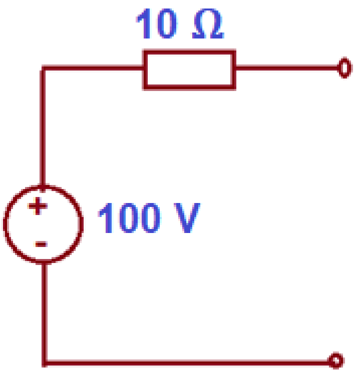
First of all, find the voltage across the terminals of the source while keeping the source terminal open. This voltage (V) is given as

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.

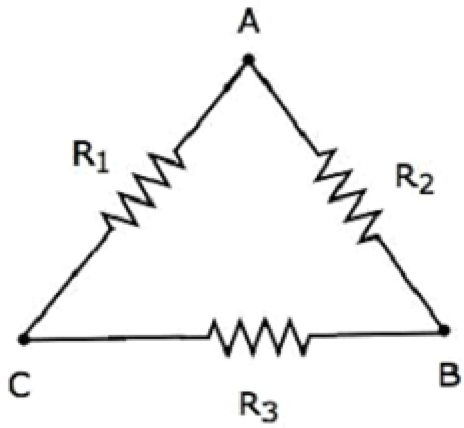


STAR-DELTA TRANSFORMATIONS

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.

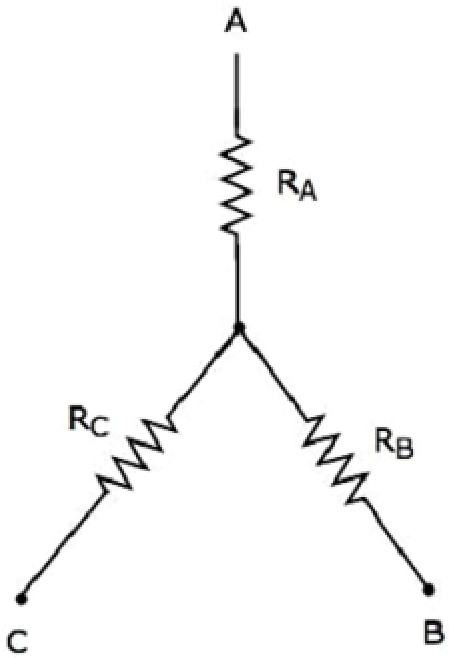
$$R_{AB} = \frac{(R_1 + R_3)R_2}{R_1 + R_2 + R_3}$$

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

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

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.

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

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

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

By adding the above three equations, we will get

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

$$\Rightarrow R_A + R_B + R_C = \frac{R_1R_2+R_2R_3+R_3R_1}{R_1+R_2+R_3}$$ **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

$$\frac{R_AR_B + R_BR_C + R_CR_A}{R_B} = R_1$$

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

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

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

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

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

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

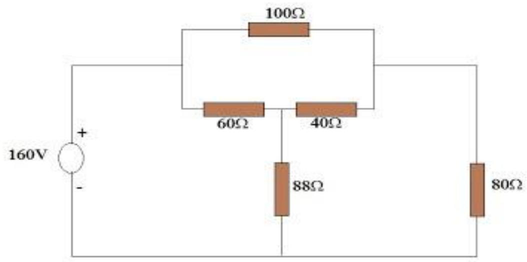


Figure 16.1

Answer:

See figure

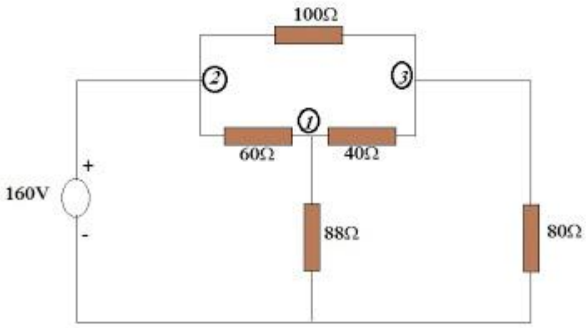


Figure 16.1 (a)

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 = 12Ω

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

R_1 = (100*60)/ 200

R_1 = 30Ω

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

R_3 = (100*40)/ 200

R_3 = 20Ω

So we can redraw the network as shown in figure

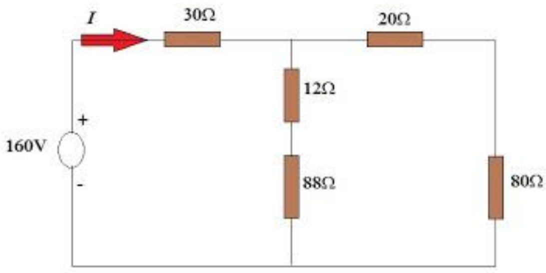


Figure 16.2

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

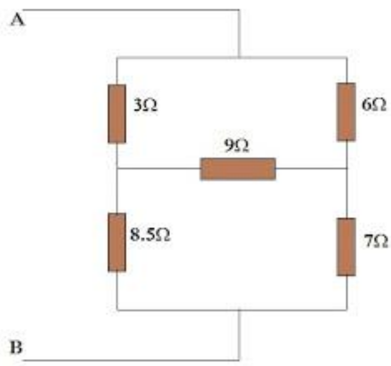


Figure 16.3

Answer:

See figure

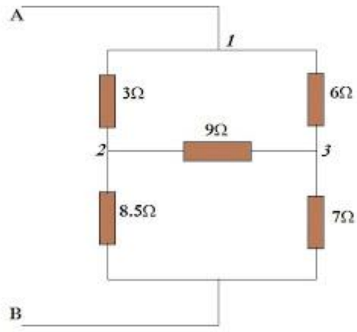


Figure 16.3(a)

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

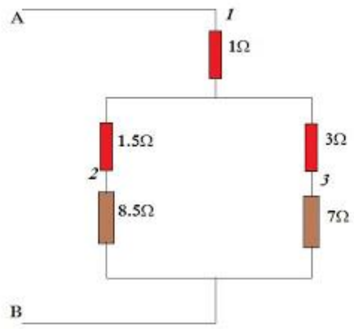


Figure 16.4

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

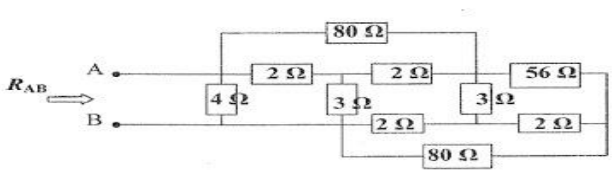


Figure 16.5

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

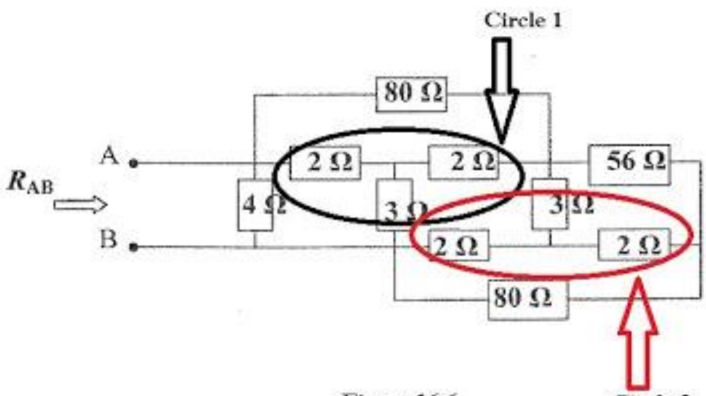


Figure 16.6

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

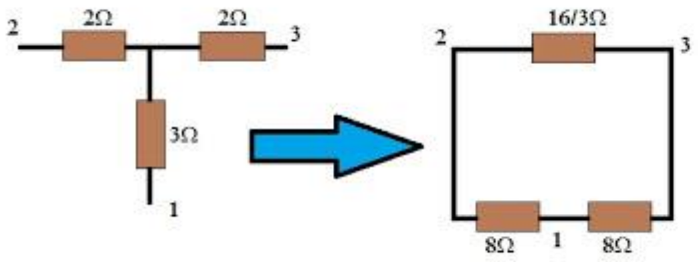


Figure 16.7

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

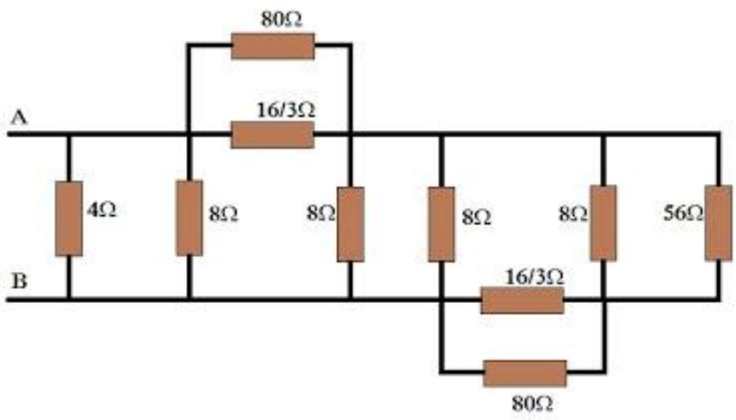


Figure 16.8

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

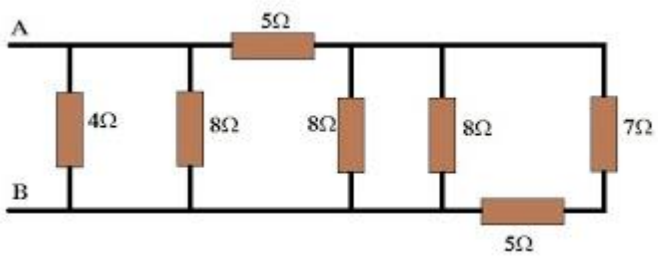


Figure 16.9

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} = 2Ω

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

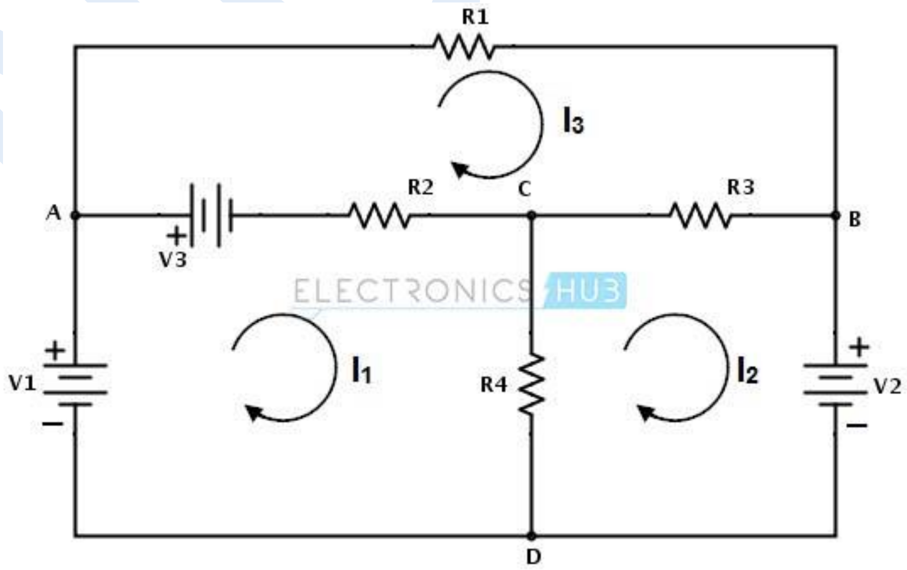
1) Check whether there is a possibility to transform all current sources in the given circuit to voltage sources.

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,

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

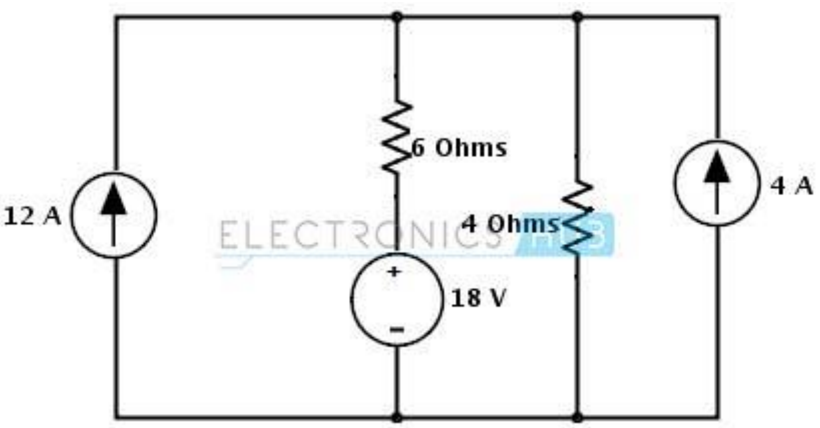
$V3 = - I1R2 - I2R3 + I3(R1 + R2 + R3)$ ………………………(3)

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:

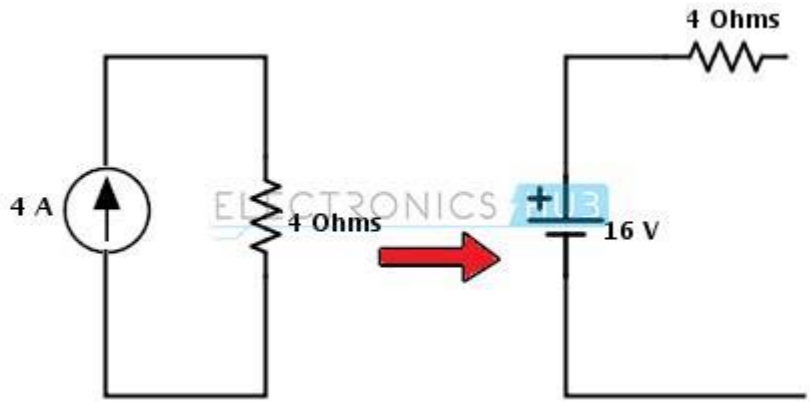
Consider the below example in which we find the voltage across the 12A current source using mesh analysis. In the given circuit all the sources are current sources.



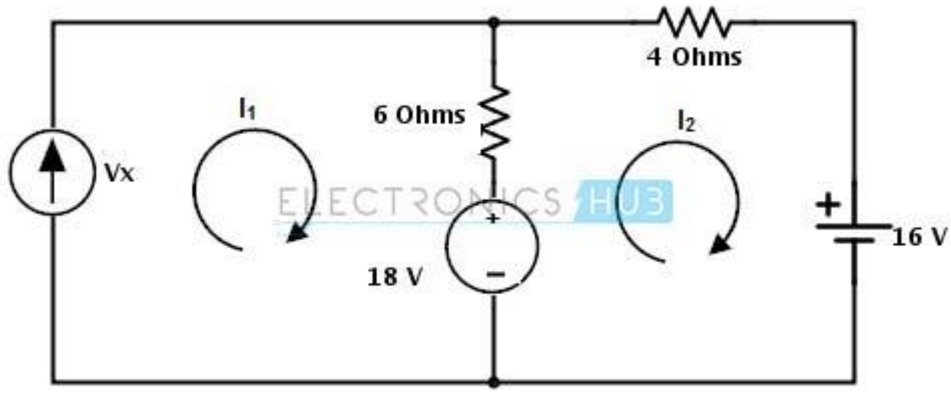
Step 1: In the circuit there is a possibility to change the current source to a voltage source on right hand side source with parallel resistance. The current source is converted into a voltage source by placing the same value of resistor in series with a voltage source and the voltage in that source 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 × (I1 − I 2) − 18 = 0

Substituting I1 = 12 A

Vx + 6I2 = 90…………………… (1)

Mesh – 2:

18 − 6 × (I 2 − I1) − 4 × I 2 − 16 = 0

2 – 10 × I2 + 6(12) = 0

I2 = 74/ 10

= 7.4 Amps

Substituting in equation 1 we get

Vx = 90 – 44.4

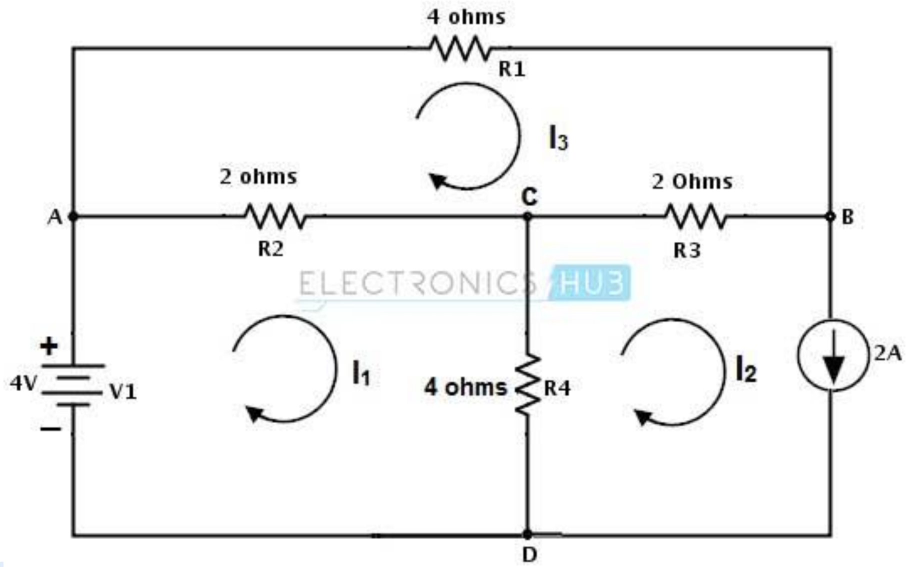
= 45.6 Volts

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

– Vc = 4I2 − 4I1 + 2I2 − 2I3 = 0

– Vc = – 4I1 + 6I2 – 2I3

But I2 = -2 A, then

– Vc = – 4I1 – 12 – 2 I3 ………………….(2)

By applying KVL to the third mesh we get

− R1 I 3 − R3 (I 3 − I 2) − R2 (I 3 − I1) = 0

−4 I3 − 2I3 + 2I2 − 2I3 + 2I1 = 0

− 8I3 − 4 + 2I1 = 0 (by substituting I2 = -2 A)

$2I1 - 8I3 = 4$ …………………(3)

By solving 1 and 3 equations we get I3 = -0.615 and I1 = 4.46

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

Vc = 28.61 V

And the branch current Iac = I1- I3

Iac = 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.

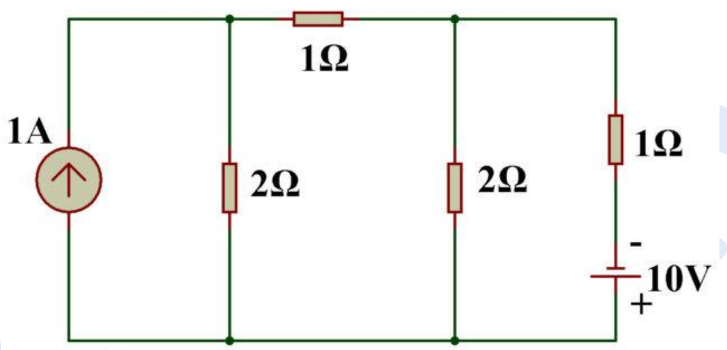


Figure: 1

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

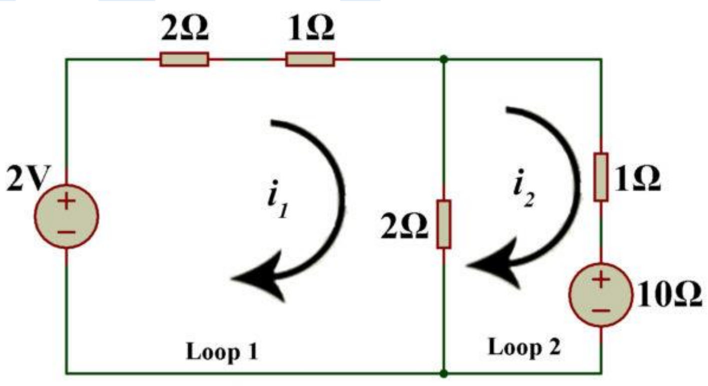


Figure: 2

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?

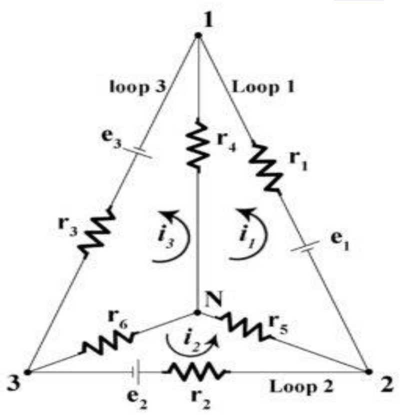


Figure: 5

Solution:

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

The loop equations are given below:

For loop-1

$$i_1r_1 + (i_1 - i - 3)r_4 + (i_1 - i_2)r_5 = e_1$$

or, $i_1(r_1 + r_4 + r_5) - i_2r_5 - i_3r_4 = e_1$ …..(i)

For loop-2

$$(i_2 - i_1)r_5 + (i_2 - i_3)r_6 + i_2r_2 = e_2$$

or, $-i_1r_5 + i_2(r_2 + r_5 + r_6) - r_6i_3 = e_2$ …..(ii)

For loop-3

$$i_3r_3 + (i_3 - i_2)r_6 + (i_3 - i_1)r_4 = e_3$$

or, $-i_1r_4 - i_2r_6 + i_3(r_3 + r_4 + r_6) = e_3$ …..(iii)

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

$i_1 = i_2 = i_3 = i$ (say)

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)

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

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

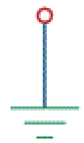
- **Nodal Analysis** is based on the application of the Kirchhoff's Current Law (KCL).
- Having 'n' nodes there will be 'n-1' simultaneous equations to solve.
- Solving 'n-1' equations all the nodes voltages can be obtained.
- The number of non reference nodes is equal to the number of Nodal equations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

Types of Nodes in Nodal Analysis

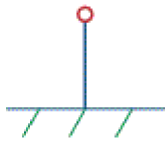
- Non Reference Node – It is a node which has a definite Node Voltage. e.g. Here Node 1 and Node 2 are the Non Reference nodes
- Reference Node – It is a node which acts a reference point to all the other node. It is also called the Datum Node.

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.



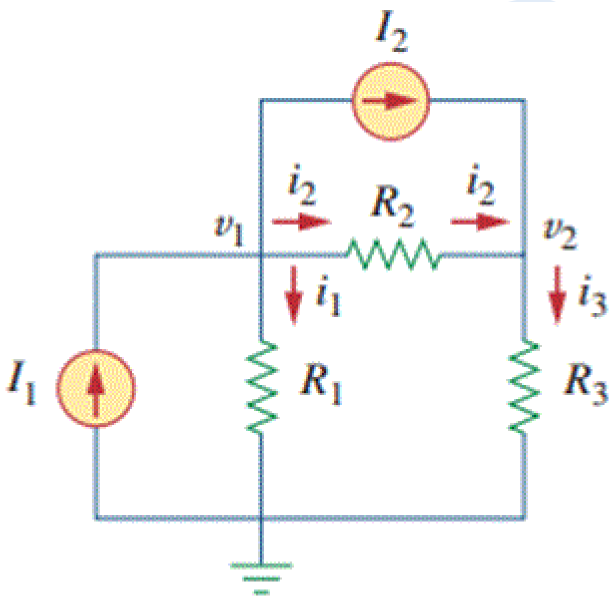
Solving of Circuit Using Nodal Analysis

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

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

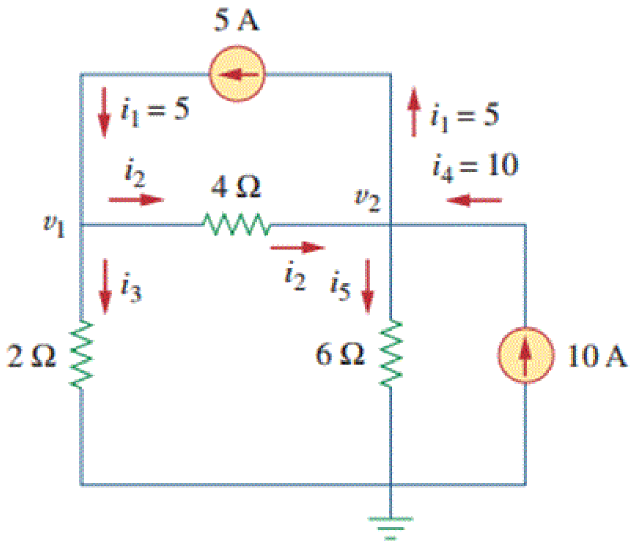
IV. After the application of Ohm's Law get the 'n-1' node equations in terms of node voltages and resistances.

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

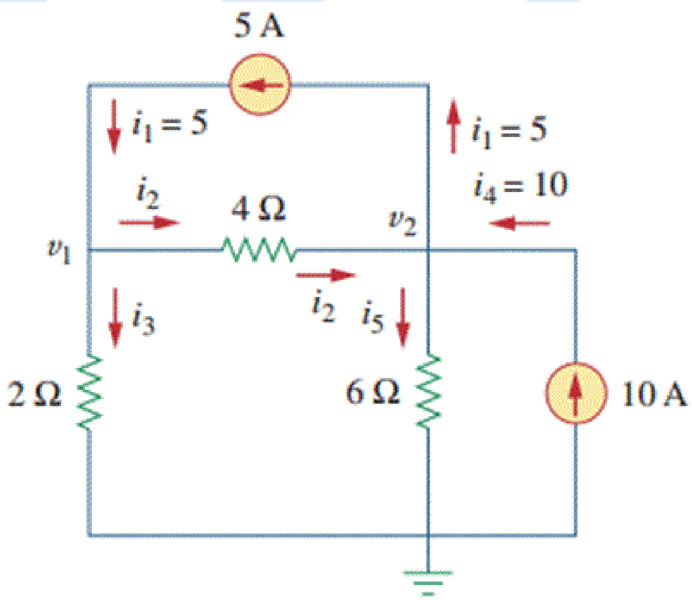
Nodal analysis with current sources is very easy and it is discussed with a example below.

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

$$3v_1 - v_2 = 20$$
$$-3v_1 + 5v_2 = 60$$
$$\Rightarrow 4v_2 = 80 \Rightarrow v_2 = 20\ Volts$$

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

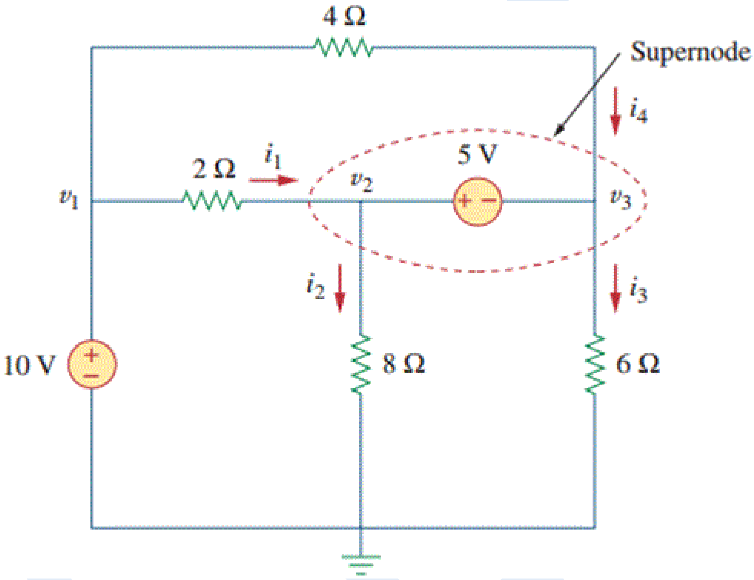
Case I. If a voltage source is connected between the reference node and a non reference node, we simply set the voltage at the non-reference node equal to the voltage of the voltage source and its analysis can be done as we done with current sources. v_1 = 10 Volts.

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

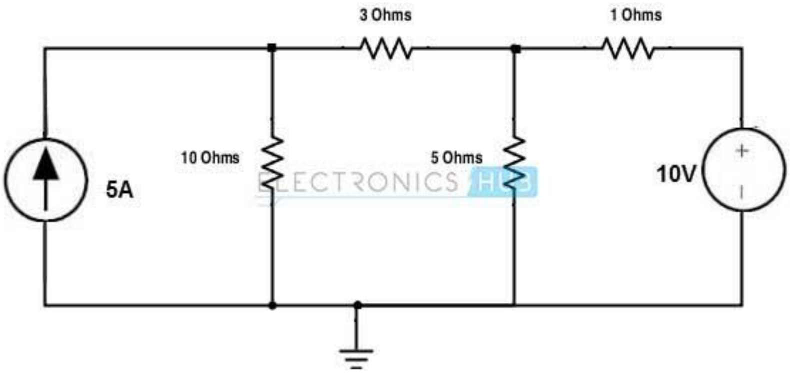
ence nodes Node – 2 and Node – 3. So here Node – 2 and Node – 3 form the Super node.

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.

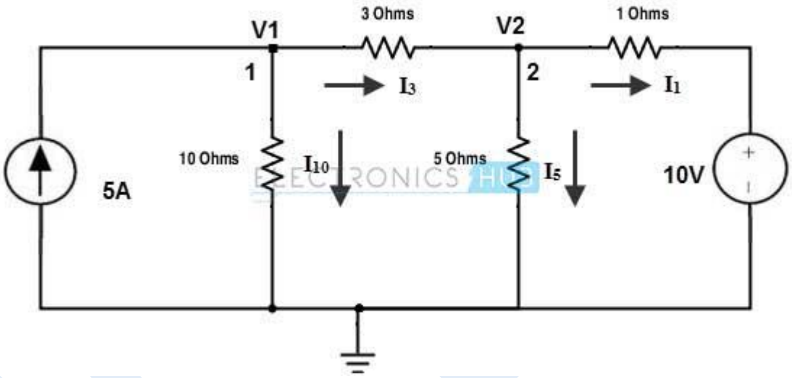
Example 1

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 labelled 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).

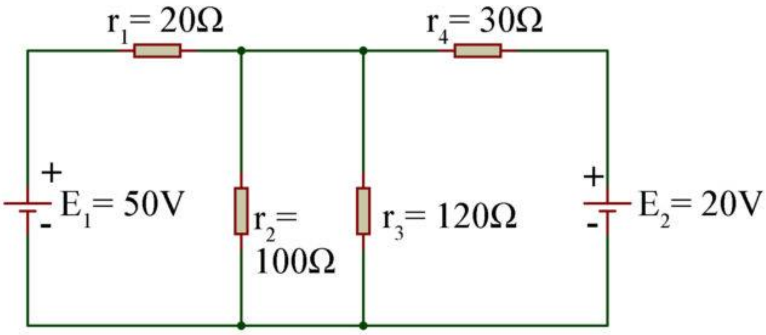


Figure: 1

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

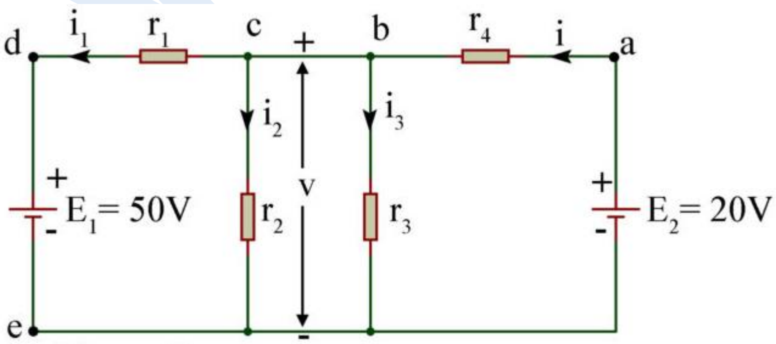


Figure: 2

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.

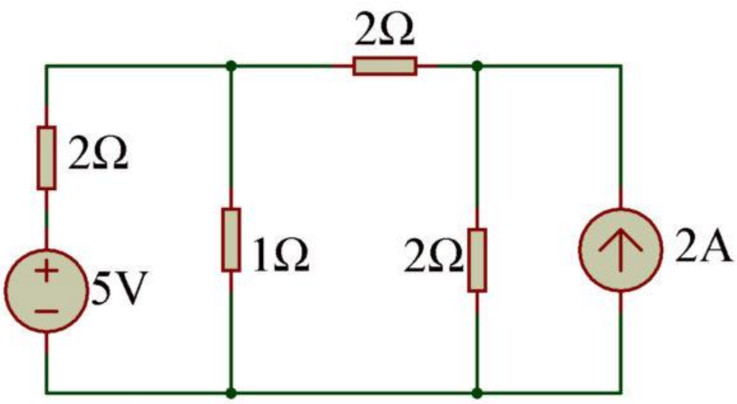


Figure: 7

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.

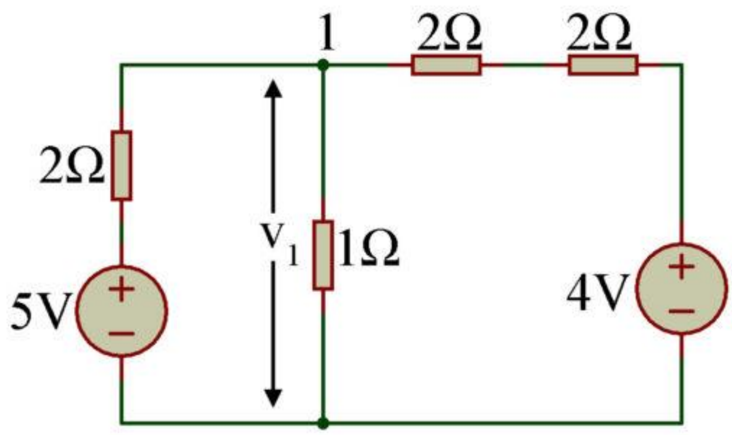


Figure: 8

∴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

CIRCUIT THEOREMS

INTRODUCTION

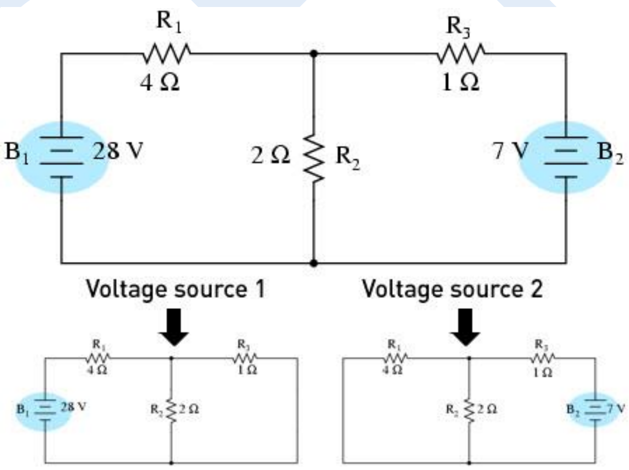
Electric circuit theorems are always beneficial to help find voltage and currents in multi-loop circuits. These theorems use fundamental rules or formulas and basic equations of mathematics to analyze basic components of electrical or electronics parameters such as voltages, currents, resistance, and so on. These fundamental theorems include the basic theorems like Superposition theorem, Tellegen's theorem, Norton's theorem, Maximum power transfer theorem, and Thevenin's theorems. Another group of network theorems that are mostly used in the circuit analysis process includes the Compensation theorem, Substitution theorem, Reciprocity theorem, Millman's theorem, and Miller's theorem.

Network Theorems

All the network theorems are briefly discussed below.

1. Super Position Theorem

The Superposition theorem is a way to determine the currents and voltages present in a circuit that has multiple sources (considering one source at a time). The superposition theorem states that in a linear network having a number of voltage or current sources and resistances, the current through any branch of the network is the algebraic sum of the currents due to each of the sources when acting independently.



Superposition theorem is used only in linear networks. This theorem is used in both AC and DC circuits wherein it helps to construct Thevenin and Norton equivalent circuit.

In the above figure, the circuit with two voltage sources is divided into two individual circuits according to this theorem's statement. The individual circuits here make the whole circuit look simpler in easier ways. And, by combining these two circuits again after individual simplification, one can easily find parameters like voltage drop at each resistance, node voltages, currents, etc.

Superposition theorem states that:

In a linear circuit with several sources the voltage and current responses in any branch is the algebraic sum of the voltage and current responses due to each source acting independently with all other sources replaced by their internal impedance.

Suppose an electrical circuit having several branches and or loads and also several source some being current source and some being voltage source. Then Superposition theorem suggests that:

If we find the branch responses (Voltage drop and Current through it) on a branch due to only of those source by ignoring effect of all other sources or replacing all other sources by their corresponding internal impedance , and repeat the process for every source on the circuit. Then the Combined responses (Voltage drop and Current through it) on a branch due to all the sources combined is the algebraic sum of responses on the branches due to each individual sources.

The process of using Superposition Theorem on a circuit:

To solve a circuit with the help of Superposition theorem follow the following steps:

1. First of all make sure the circuit is a linear circuit; or a circuit where Ohm's law implies, because Superposition theorem is applicable only to linear circuits and responses.

2. Replace all the voltage and current sources on the circuit except for one of them.While replacing a Voltage source or Current Source replace it with their internal resistance or impedance. If the Source is an Ideal source or internal impedance is not given then replace a Voltage source with a short ; so as to maintain a 0 V potential difference between two terminals of the voltage source. And replace a Current source with an Open ; so as to maintain a 0 Amps Current between two terminals of the current source.

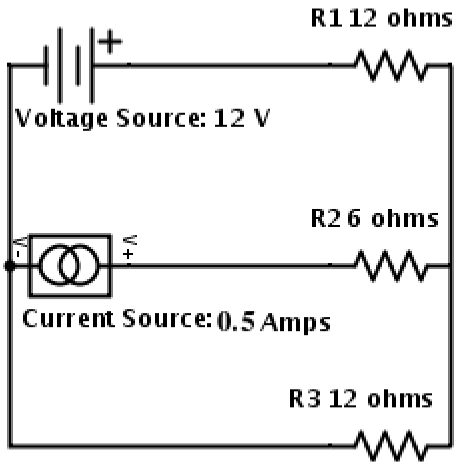
3. Determine the branch responses or voltage drop and current on every branches simply by using KCL , KVL or Ohm's Law.

4. Repeat step 2 and 3 for every source the circuit have.

5. Now algebraically add the responses due to each source on a branch to find the response on the branch due to the combined effect of all the sources.

Superposition Theorem in Action:

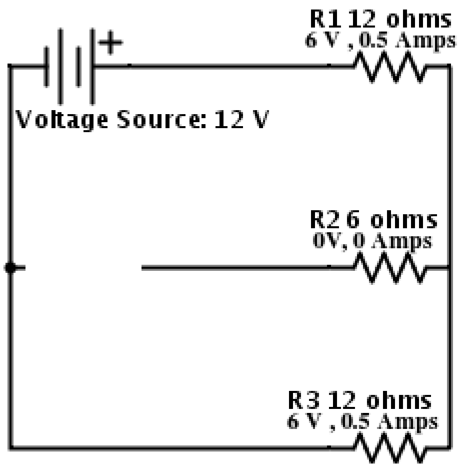
In the following circuit:



We can use Superposition Theorem to solves the circuit as following:

Let us first Find Responses on the branches due to the Voltage source:

To Remove the Current source it is opened , which converts the circuit into a simple voltage divider circuit and the responses can be calculated simply by using ohm's law as following:



Thus The responses due to The voltage source are:

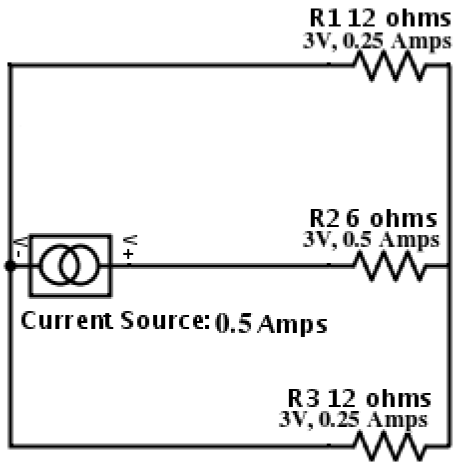
On R1 ; Voltage Drop = 6V , Current = 0.5 Amps

On R2 ; Voltage Drop = 0V , Current = 0 Amps

On R3 ; Voltage Drop = 6V , Current = 0.5 Amps

Now let us find the responses on various branches due to the current source:

To remove the Voltage source it is shorted which converts the circuit into a simple network of parallel and series connection of resistors ; and the responses can be easily calculated using ohm's law as following:



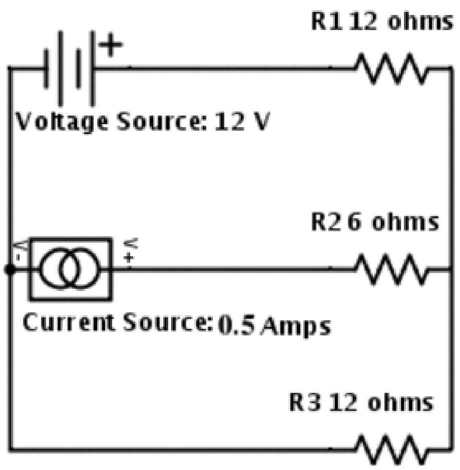
Thus The responses due to the current source are:

On R1 ; Voltage Drop = 3V , Current = 0.25 Amps

On R2 ; Voltage Drop = 3V , Current = 0.5 Amps

On R3 ; Voltage Drop = 3V , Current = 0.25 Amps

Now finally to find the responses on each branch due to the combined effect of both current source and voltage source we add the individual responses.



So,

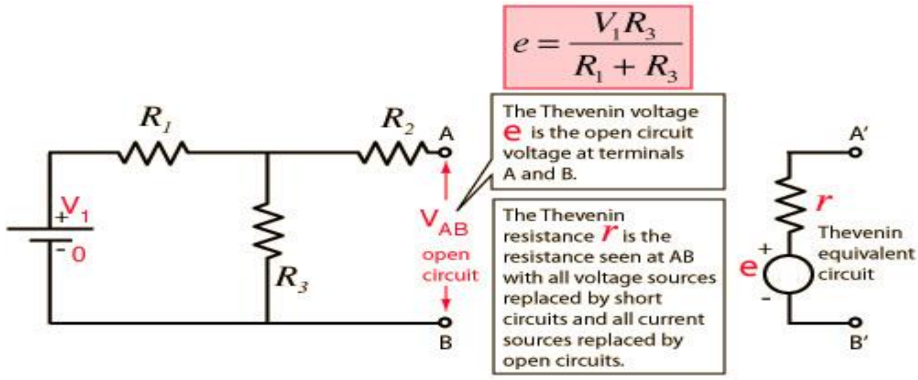
On R1 ; Voltage Drop = (6+3)V = 9V , Current = (0.5+0.25) Amps = 0.75 Amps

On R2 ; Voltage Drop = (0+3)V = 3V , Current = (0+0.5) Amps = 0.5 Amps

On R3 ; Voltage Drop = (6+3)V = 9V , Current = (0.5+0.25) Amps = 0.75 Amps

2. Thevenin's Theorem

Statement: A linear network consisting of a number of voltage sources and resistances can be replaced by an equivalent network having a single voltage source called Thevenin's voltage (Vthv) and a single resistance called (Rthv).



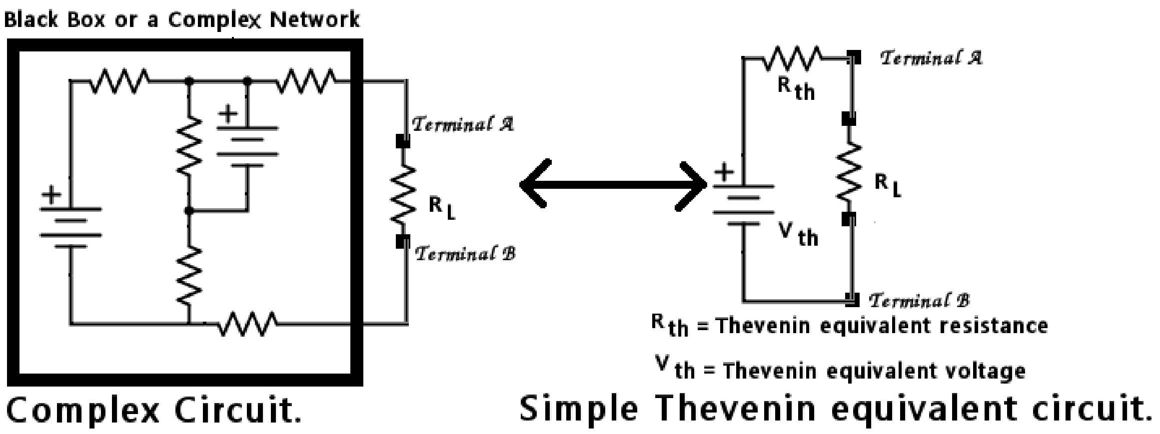
Thevenin's Theorem

The above figure explains how this theorem is applicable for circuit analysis. Thevinens voltage is calculated by the given formula between the terminals A and B by breaking the loop at the terminals A and B. Also, Thevinens resistance or equivalent resistance is calculated by shorting voltage sources and open circuiting current sources as shown in the figure.

This theorem can be applied to both linear and bilateral networks. It is mainly used for measuring the resistance with a Wheatstone bridge.

Any network or combination of sources and resistors with two terminals can be replaced by the equivalent circuit with a voltage source and a resistor in series. Where the voltage source of equivalent circuit is open circuit voltage at the terminals , and the resistance of the series resistor of equivalent circuit is the value obtained by dividing the equivalent voltage source by the short circuit current on the terminals.

Using Thévenin's theorem we can easily calculate the branch responses on a certain branch of a complex electrical network.



Thevenin Equivalent

Thevenin equivalent circuit is the equivalent circuit of a complex network with the Thevenin voltage source and Thevenin resistor in series of the Thevenin voltage source and the load.The process of finding the Thevenin equivalent is also sometimes called Thevenization of a circuit and the Thevenin equivalent circuit is called Thevenized circuit.

Thevenin Voltage

Thevenin equivalent voltage is the output voltage in the terminals of the network , when the terminal is open or without any load resistor. It is denoted by V_{th}.

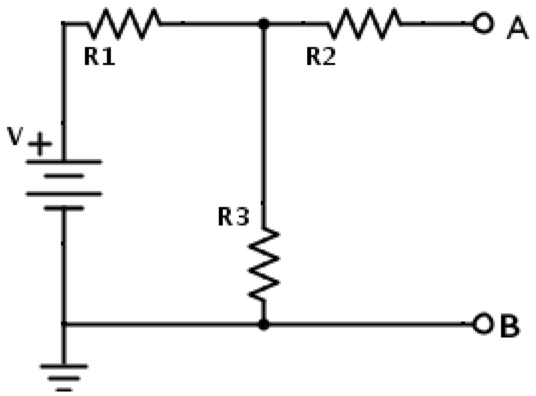
Thevenin Resistance

Thevenin equivalent resistance is the resistance measured through the two points of the terminal after all internal voltage sources are replaced with a short and all internal current sources are replaced with an open.

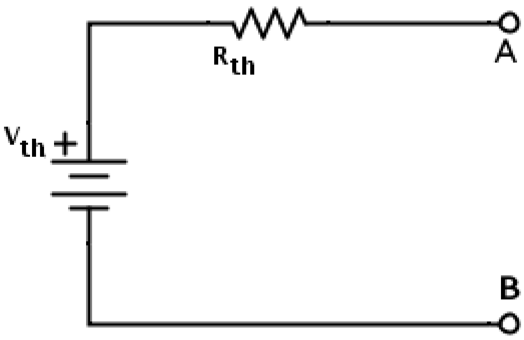
Thevenin resistance can also be calculated mathematically by dividing the Thevenin voltage by the current flowing through the terminals with a short between terminals ; this particular mathematical technique can specially be used to calculate Thevenin resistance when the circuit contains dependent sources.

It is denoted by V_{th}.

For Example consider the following circuit:



The Thevenin equivalent of the above circuit is:



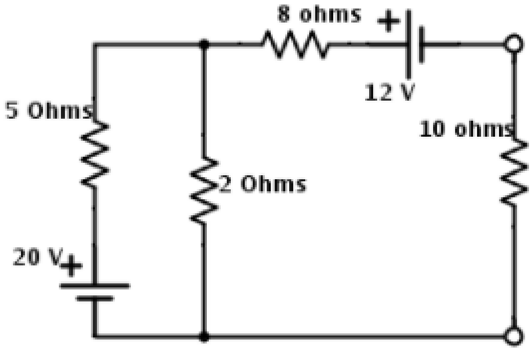
Where,

$V_{th} = V_{AB}$ = the voltage measured through the terminals A and B in the first circuit.

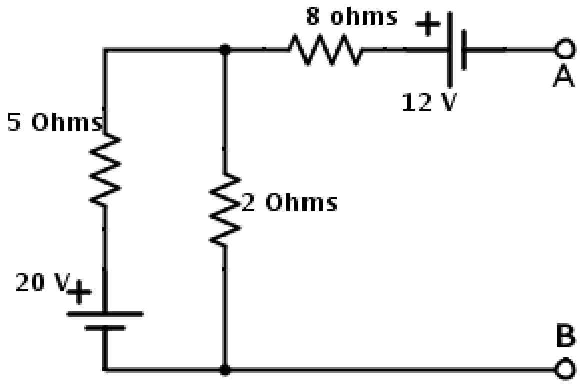
and $R_{th} = R_2 + \frac{1}{\frac{1}{R_1} + \frac{1}{R_3}}$ = The Resistance measured through the terminal A and B in the first circuit after the voltage source is replaced by a short.

Thévenin's theorem example:

Using Thévenin's theorem let us find the voltage drop and current through the 10 Ohms resistor in the following circuit:



Finding the V_{th}:

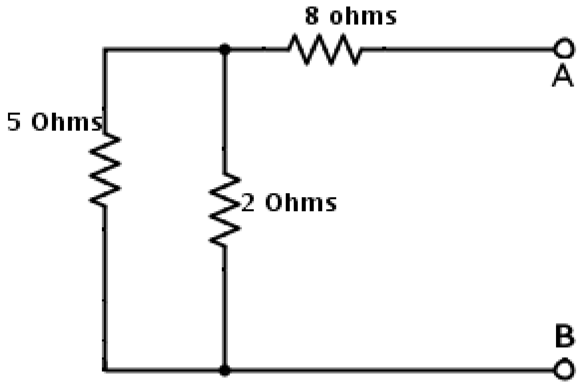


$V_{th} = V_{AB}$ = Voltage at 8 Ohms resistor – 12 V

Finding Voltage at 8 Ohms resistor , using voltage divider formula: $\frac{2}{2+5} \times 20 = 5.71V$

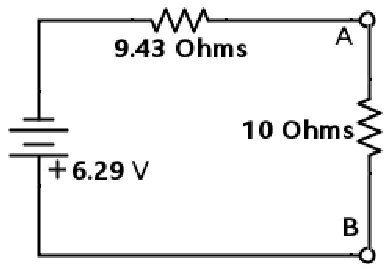
Thus , $V_{th} = V_{AB}$ =5.71 – 12 = -6.29 V

Now finding R_{th}:



$R_{th} = R_{AB} = 8\Omega + \frac{1}{\frac{1}{5}+\frac{1}{2}}\Omega = 9.43\Omega$

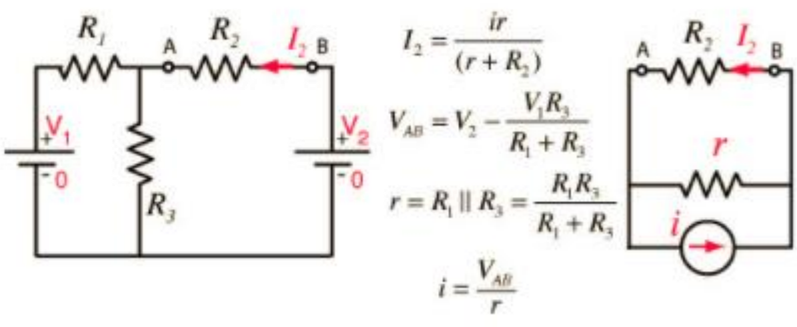
Thus the Thevenin Equivalent of the given circuit is:



Thus the Voltage drop Through 10 Ohms resistor = 3.24 Voltage , and the Current flowing through it = 0.32 Amps

3. Norton's Theorem

This theorem states that any linear circuit containing several energy sources and resistances can be replaced by a single constant current generator in parallel with a single resistor.



Norton's Theorem

This is also the same as that of the Thevinens theorem, in which we find Thevinens equivalent voltage and resistance values, but here current equivalent values are determined. The process of finding these values is shown as given in the example within the above figure.

Norton's Theorem is a network reduction electrical network analysis technique which can be used to analyse the current through a branch in complex network of linear electronic components. Norton's theorem can be thought as an alternative of Thévenin's theorem in the sense that the Thévenin's theorem reduces a complex network into a voltage source and a series resistance ; and the Norton's theorem reduces a complex network into a current source and a parallel resistance .

Norton's Theorem was independently developed by Hans Ferdinand Mayer and Edward Lawry Norton in 1926 therefore the theorem is also sometimes called as Mayer–Norton theorem.

Norton's Theorem states that:

Any linear electrical network with any numbers of sources (voltage or current) and components ; is equivalent to a current source with a resistor in parallel when viewed from the network's output terminals.

Where , The equivalent current source is the current flowing through the output terminals when it is short-circuited and the equivalent resistance is the resistance as observed on the output terminals when all the voltage and current sources in the network are replaced by their respective internal resistances.

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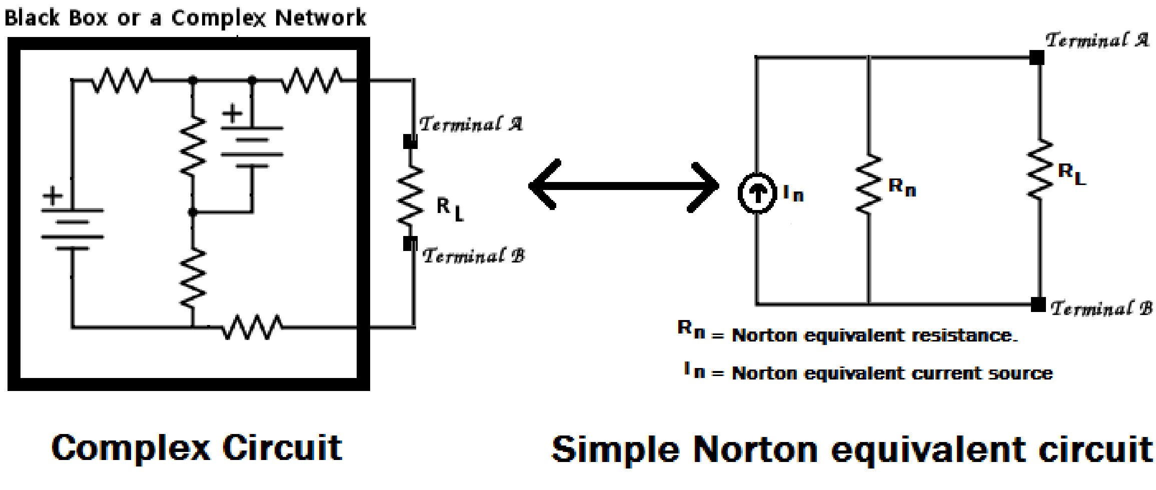


Norton's Theorem

Norton Equivalent

Norton's equivalent or Norton equivalent circuit is a reduced version of or equivalent circuit of a complex electrical network circuit, derived in accordance with the Norton's Theorem. The Norton equivalent circuit contains a current source with a resistance in parallel with it, which can be calculated as stated below:

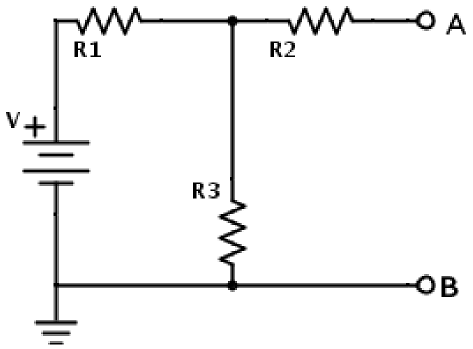
Norton Current

Norton equivalent current is the current observed to be flowing through the terminals , when the terminals are short circuited. To calculate the Norton current either a observation is made by short circuiting the output terminals and measuring the current through it , or various mathematical techniques like Ohm's law , KCL and KVL are used.

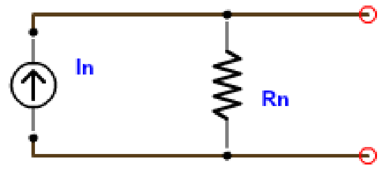
Norton Resistance

Norton equivalent resistance is the resistance measured through the output terminal after all internal voltage and current source are replaced by their internal resistance. For ideal voltage sources, they are replaced with a short and for ideal current sources, they are replaced with an open. Note that: The Norton Resistance is equal to the Thevenin Resistance.

For example consider the following example:



The Norton Equivalent of the above circuit is:



Norton Equivalent Circuit

Where,

-

Where,

I_n = Norton current = current flowing through the terminals when the terminals are short circuited = Current flowing through R_2 when the terminal A and B are short circuited.

So, $$I_n = I_{R_2} = \frac{R_3}{R_2 + R_3} \times \frac{V}{R_1 + \frac{R_2 \times R_3}{R_2 + R_3}}$$

" $\frac{V}{R_1 + \frac{R_2 \times R_3}{R_2 + R_3}}$ *is the current flowing through the source. and multiplying it by the* $\frac{R_3}{R_2 + R_3}$ *gives the current flowing through* R_2

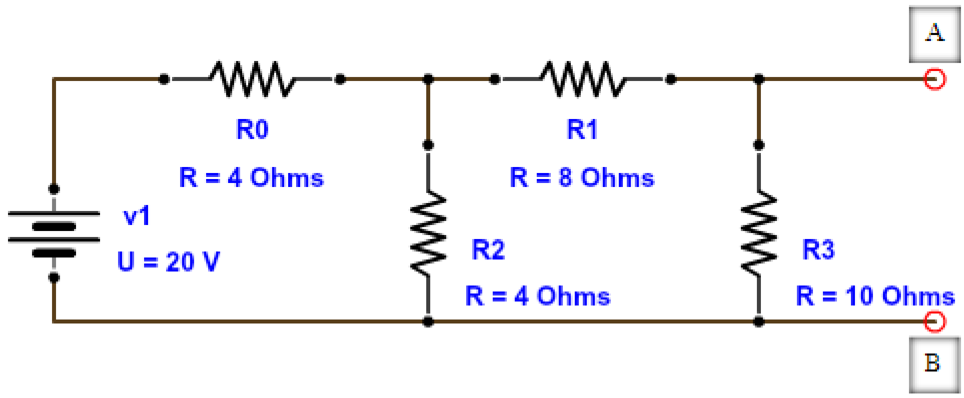
And,

R_n = Norton Resistance = Internal resistance of the circuit as observed from the terminals after removing the internal sources with their internal resistance.

Or, $$R_n = R_2 + R_1 || R_3 = R_2 + \frac{R_1 \times R_3}{R_1 + R_3}$$

Norton's Theorem Example:

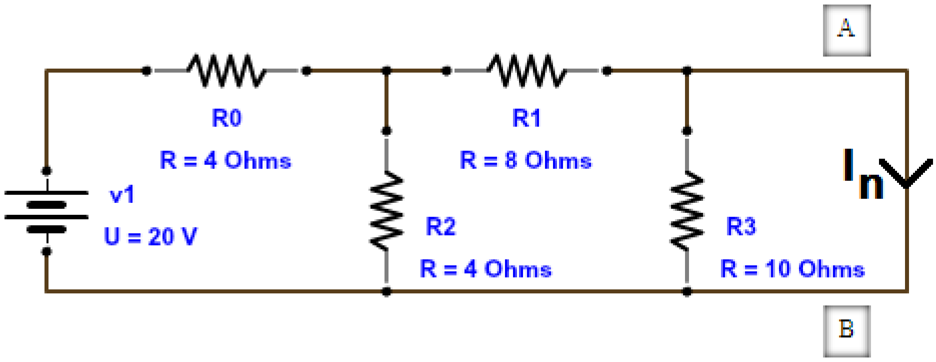
Question: Using Norton's Theorem find the Norton equivalent circuit of the following circuit. And also find the current flowing through the load when the load is a 5 ohms resistor.



Norton Theorem Example.

Here,

To find Norton's current I_n :



Calculating Norton Current

Here, The output terminals are short circuited. The current flowing through the short; In; is the Norton equivalent current.

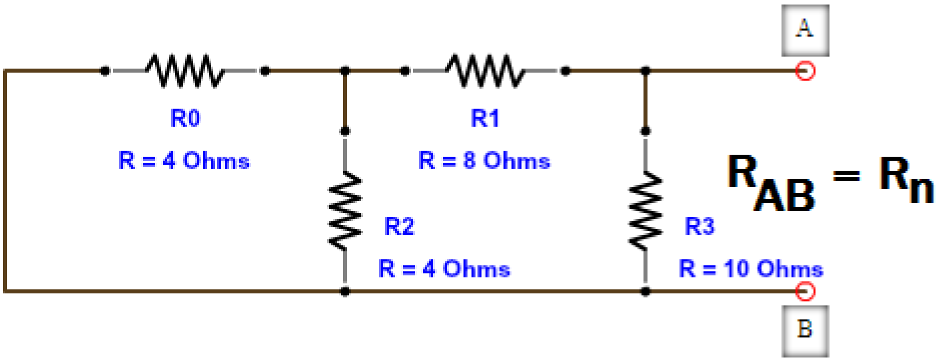
Load resistance to the source V1 = $4 + 8||4 = 4 + \frac{8 \times 4}{8 + 4} = \frac{20}{3}\Omega$

So, Current through the source V1 = $\frac{20V}{\frac{20}{3}\Omega} = 3A$

So Now,

I_n = Current flowing through 8 ohms resistor = $\frac{4}{8+4} \times 3A = 1A$

To find Norton's Resistance R_n:



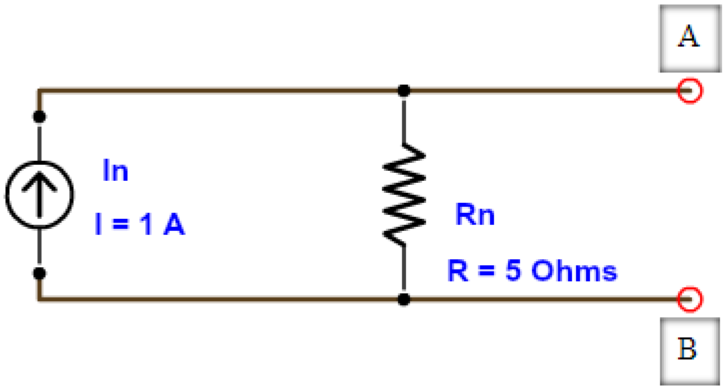
Calculating Norton Resistance

he Voltage source is replaced by it's internal resistance which is zero ohms since it is not stated.

And ,

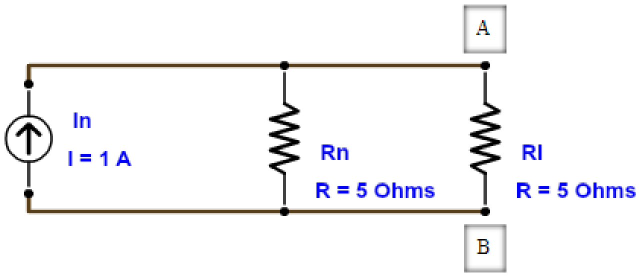
$$R_n = R_{AB} = 10||(8 + 4||4) = 10||\left(8 + \frac{4 \times 4}{4 + 4}\right) = 10||10 = \frac{10 \times 10}{10 + 10} = 5\Omega$$

Thus the Norton Equivalent Circuit of the given circuit is:



Norton Equivalent Circuit

And when a 5 Ohms load is connected to the output:



Norton Theorem example with Load

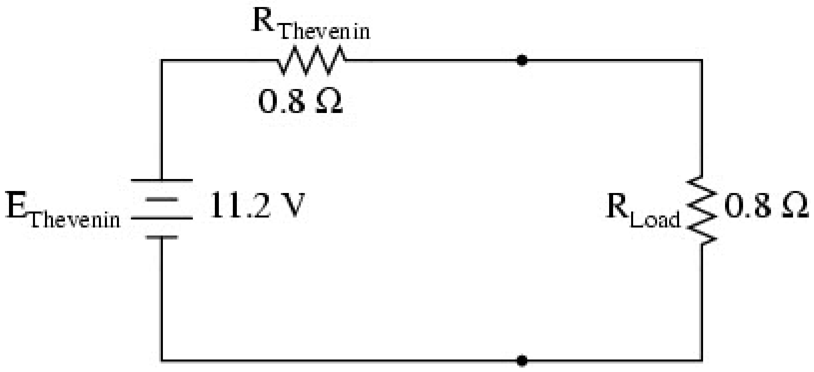
The current through the Load resistance $R_L = 5\Omega$ is I_L

and

$$I_L = \frac{5}{5+5} \times 1A = 0.5A$$

4. Maximum Power Transfer Theorem

This theorem explains the condition for the maximum power transfer to load under various circuit conditions. The theorem states that the power transfer by a source to a load is maximum in a network when the load resistance is equal to the internal resistance of the source. For AC circuits load impedance should match with the source impedance for maximum power transfer even if the load is operating at different power factors.



Maximum Power Transfer Theorem

For instance, the above figure depicts a circuit diagram wherein a circuit is simplified up to a level of source with internal resistance using Thevenin's theorem. The power transfer will be maximum when this Thevinens resistance is equal to the load resistance. The Practical application of this theorem includes an audio system wherein the resistance of the speaker must be matched to the audio power amplifier to obtain maximum output.

Maximum power theorem is a theorem or technique used in Electrical Network Analysis and Electrical circuit designing. It was invented by a German engineer Moritz von Jacobi in 1840. He invented the theorem in the process of finding a way to maximize the output of the battery to a motored boat which he designed to travel in the river Neva ; Thus the theorem is also sometimes refereed to as Jacobi's Law.

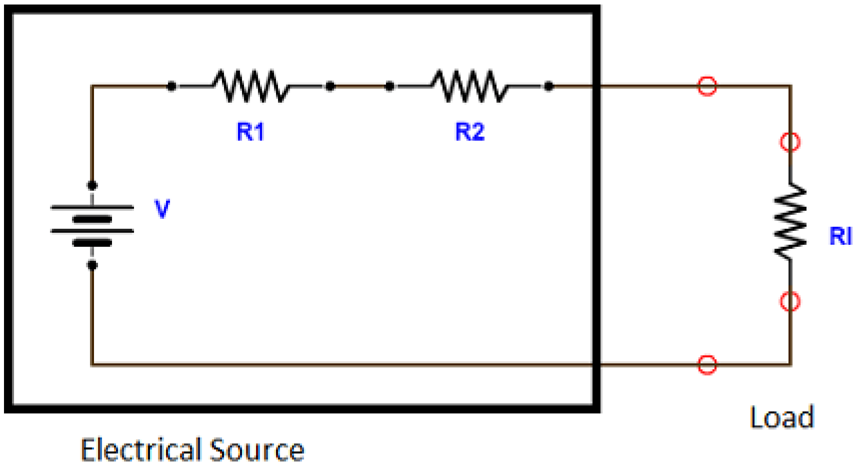
Maximum power transfer theorem deals with the power transferred to the load on a circuit with a network of various sources or components on it. The maximum power transfer theorem defines the condition under which the maximum power is transferred to the load in a circuit.

Note: Here we are talking about maximum power transferred to the load only, not about the maximum power transferred to the load and internal components or resistance of the source combined, Under the condition of Maximum power transfer we only deal with the power transferred to the load and does not consider the power dissipated in internal circuits or resistance of the source so we are not talking about the maximum efficiency of power transfer but instead maximum possible power transfer from a source to a load.
The Maximum Power Transfer Theorem states that:

The power transferred from a source or circuit to a load is maximum when the resistance of the load is made equal or matched to the internal resistance of the source or circuit providing the power to the load.

For Example:

In the following Circuit:



maximum power transfer theorem example

According to maximum power transfer theorem the maximum power will be yielded to the load RL when RL is equal to the internal resistance of the circuit or R1+R2.

The Maximum power transfer theorem holds true in any kind of circuit may it be linear, non-linear, active, DC or AC. In the case of DC circuits the load resistance is matched with internal resistance of the source by making both resistance equal and in case of AC the Load impedance is matched with the internal impedance of the circuit or source by making the load impedance the complex conjugate of the source impedance. For eg: load impedance will be $R_1 - jX$ if the internal impedance of the source is $R_1 + jX$

Proof of Maximum Power Transfer Theorem:

Maximum power transfer theorem can be proved in DC networks or resistive circuits as following:

Let,
V = EMF supplied to the load.

R_L = Load resistance.

R_i = Internal resistance of the source.

I = Current flowing through the load, internal resistance and the source of the circuit.

P_L = Power transferred to the load.
P_i = Power dissipated at internal resistances.

Then,

Power transferred to the load = $P_L = I^2 R_L$

or,

$$P_L = \left(\frac{V}{R_i + R_L}\right)^2 \times R_L = \frac{V^2}{\frac{R_i^2}{R_L} + 2R_i + R_L}$$

Now using the theorems of Differential calculus , If we keep the RL variable and want to calculate the maximum value of PL then we need to differentiate the PL with respect to RL and equate it with zero. Thus,

Under Maximum power transfer to load condition:

$$\frac{d}{dR_L}P_L = \frac{d}{dR_l}\frac{V^2}{\frac{R_i^2}{R_L} + 2R_i + R_L} = 0$$

or,

$$-\frac{R_i^2}{R_L^2} + 1 = 0$$

or,

$$R_i = R_L$$

And in AC networks using same mathematical technique we can prove:

if,
$Z_i = R_i + X_i$ = Internal impedance of reactive circuits.

$Z_L = R_L + X_L$ = Load impedance.

Then, Under the condition of maximum power transfer to load:

$Z_i = Z_l$, $R_i = R_L$ and $X_i = -X_L$

Power Transfer Efficiency:

Power transfer efficiency is the efficiency of any source or circuit in transferring it's power to the load. Or it is the ratio of power transferred to the load over total power transferred by the source. It is denoted by the Greek letter η

And Mathematically: $\eta = \frac{P_L}{P_T}$, Where $P_L$is the power transferred to the load and P_T is the total power transferred by the source.

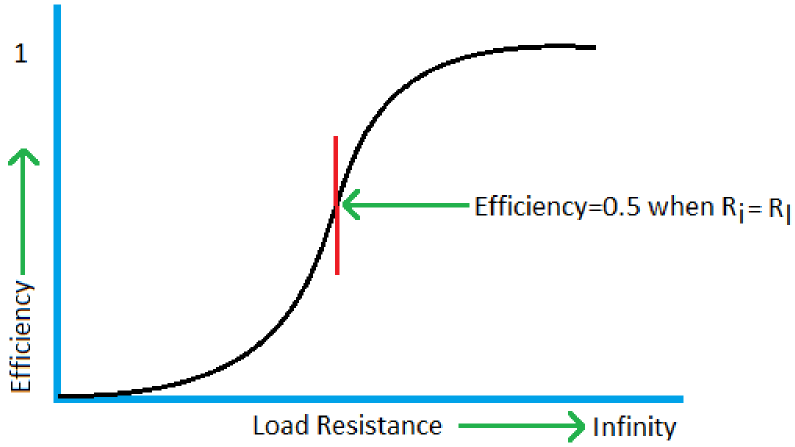
We can expand this expression as:

$P_L = I^2 R_L$ and $P_T = P_L + P_I = I^2 R_L + I^2 R_I$, where, I is the total current flowing through the circuit or Thevenin equivalent of the circuit, $P_I$is the power dissipated in internal circuits of the source. Thus,

$$\eta = \frac{P_L}{P_T} = \frac{I^2 R_L}{I^2 R_L + I^2 R_I} = \frac{R_L}{R_L + R_I} = \frac{1}{1 + \frac{R_I}{R_L}}$$

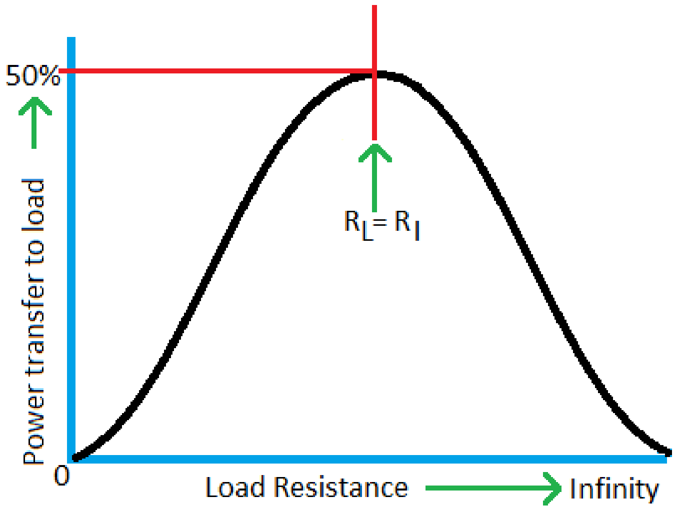
As we know that under the condition of maximum power transfer $R_L = R_I$, we can derive from above formula that the efficiency under the condition of maximum power transfer is only 0.5.

The overall efficiency decreases if the R_L is kept very low and it increases up to one when the R_L is increased to infinity as shown on the graph below:



Graph: Power transfer efficiency Vs Load resistance

And the power transferred to load becomes minimum when R_L is kept very low and very high. The maximum power transfer to load is obtained when $R_L = R_I$. As shown on the following graphs:



Graph: Power transfer to load Vs Load Resistance.

Applications of Maximum Power Transfer Theorem:

The Maximum Power Transfer Theorem has a wide range of usage on real life situation. The theorem is used to maximize the power output to a load from any circuit. So they can be used to design circuits where the maximum output performance is desired for example to match an Amplifier with a Loudspeaker to yield maximum power to the speaker and thus produce maximum sound. In some situations Transformer Coupling are also used to yield maximum power to the load when the matching of Load and Source impedance is not possible for example is the amplifier is of 1000 Ohms and the speaker if of 10 ohms.

The application of Maximum Power Theorem is done only under the conditions when the maximum performance is desired over the overall efficiency of the circuit because as we discussed above the efficiency of a circuit under maximum power transfer condition is only 0.5. So, Maximum power transfer theorem is applied in radio electronics; for example: In Antenna Signal amplifier for radio and TV receivers; and various other fields where maximum performance is required but the maximum efficiency is not desired.

Elaboration of Maximum power transfer theorem with example:
let an amplifier circuit provides 20 voltage with 5 ohms internal resistance.

If you connect a 1 ohm speaker to the circuit:

Total current flowing through the system(internal resistance and speaker) = 20 V / (5+1) ohm = 3.333 amps.
Total power usage by the whole system = I^2 * Total resistance = 1^2 * 6 = 66.6666 watts
Power usage by speaker = I^2 * speaker resistance = 11.11 watts.
Power usage by internal resistance = I^2 * internal resistance = 55.55 watts
That means 16% of power is transferred to speaker.

Now, If you connect a 5 ohm speaker to the circuit:

Total current flowing through the system (internal resistance and speaker) = 20 V / (5+5) ohm = 2 amps.
Total power usage by the whole system = I^2 * Total resistance = 2^2 * 10 = 40 watts.
Power usage by speaker = I^2 * Speaker resistance = 20 watt.
Power usage by internal resistance = I^2 * Internal resistance = 20 watts again.
That means 50% power is transferred to speaker.

Again, If you connect a 15 ohm speaker:

Total current flowing through the system(internal resistance and speaker) = 20 V / (5+15) ohm = 1 amps.
Total power usage by the whole system = I^2 * Total resistance = 1^2 * 20 = 20 watts.
Power usage by speaker = I^2 * speaker resistance = 15 watts.
Power usage by internal resistance = I^2 * internal resistance = 5 watts
That means 66% of power is transferred to speaker.

In above condition when the one ohm resistance load is connected only 16% power is transferred to the speaker which is 11.11 watts! in second condition when the speaker resistance is matched with internal resistance 50% power is transferred to the speaker which is 20 watts. This is the condition of maximum power transfer. And again in third condition with 15 ohm speaker 15 watt power is transferred to the speaker but it is 66% of the total power transferred.

MODULE III

AC CIRCUITS

Introduction

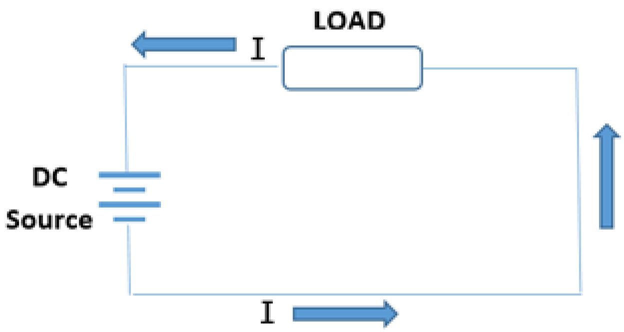
An electrical circuit is a complete conductive path through which electrons flow from the source to the load and back to the source. The direction and magnitude of the electrons flow however depend on the kind of source. In Electrical Engineering, there are basically two types of voltage or current (Electrical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

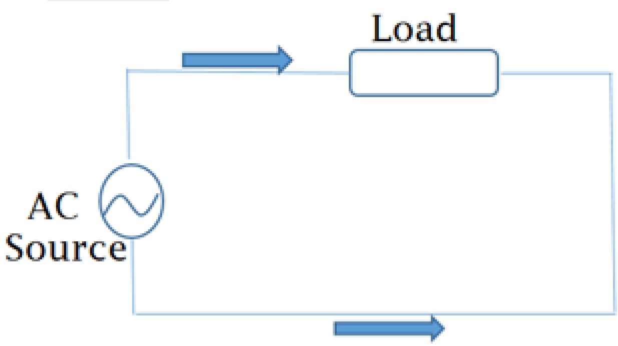
Alternating Current VS Direct Current (AC vs DC)

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.



DC Current Flowing in one Direction



AC Current alternating at Intervals

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.

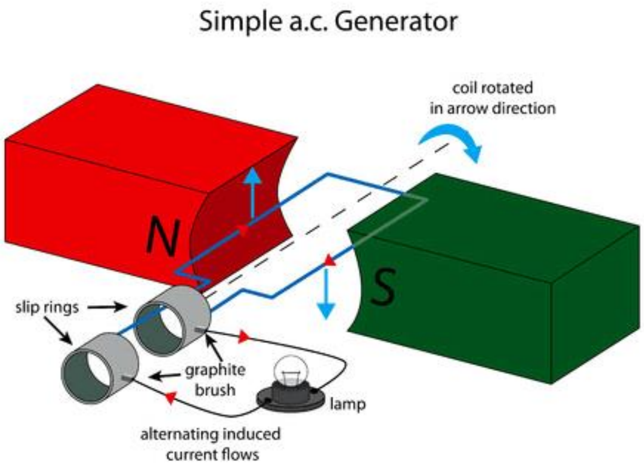
Comparison Basis	AC	DC
Energy Transmission Capacity	Travels over long distance with minimal Energy loss	Large amount of energy is lost when sent over long distances
Generation Basics	Rotating a Magnet along a wire.	Steady Magnetism along a wire
Frequency	Usually 50Hz or 60Hz depending on Country	Frequency 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 (Single Coil AC Generator)

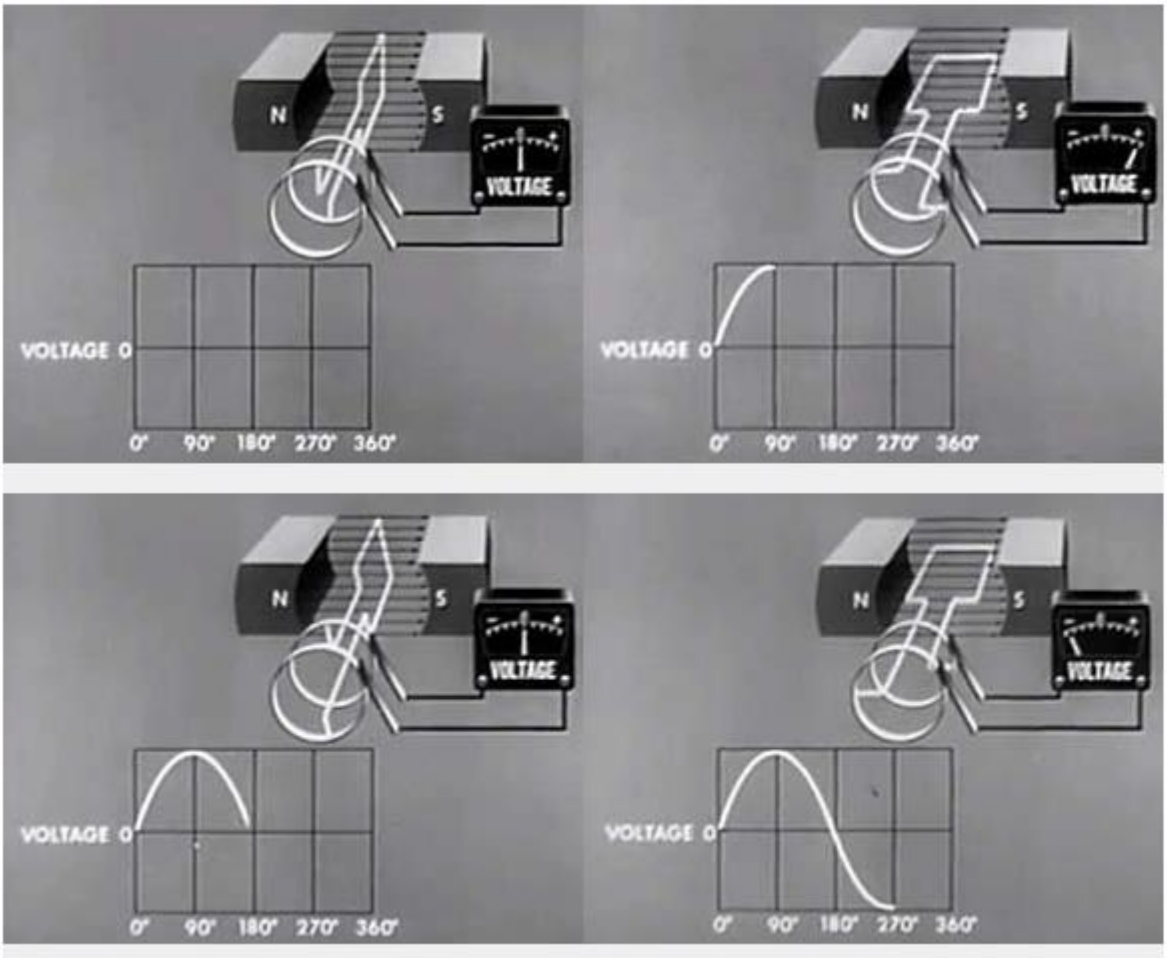
The **principle around AC generation** is simple. If a magnetic field or magnet is rotated along a stationary set of coils (wires) or the rotation of a coil around a stationary magnetic field, an Alternating current is generated using an AC generator(Alternator).

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;



From the images shown above, we can deduce that, **certain number of magnetic field lines will be cut as the armature rotates, the amount of 'lines cut' determines the voltage output**. With each change in the angle of rotation and the resultant circular motion of the armature against the magnetic lines, the amount of 'magnetic lines cut' also changes, hence the output voltage also change. For instance, the magnetic field lines cut at zero degree is zero which makes the resultant voltage zero, but at 90 degrees, almost all the magnetic field lines are cut, thus maximum voltage in one direction is generated in one direction. The same holds at 270 degrees only that it's generated in the opposite direction. There is thus a resultant change in the voltage as the armature rotates within the magnetic field leading to the formation of a **sinusoidal waveform**. The resultant induced voltage is thus sinusoidal, with an angular frequency ω measured in radians per seconds.

The Induced current in the setup above is giving by the equation:

I = V/R

Where V= NABwsin(wt)

Where N = Speed

A = Area

B = Magnetic field

w = Angular frequency.

Real AC generators are obviously more complex than this but they work based on the same principles and laws of electromagnetic induction as described above. Alternating current is also generated using certain kind of transducers and oscillator circuits as found in inverters.

Alternating current

Direct current (DC) circuits involve current flowing in one direction. In alternating current (AC) circuits, instead of a constant voltage supplied by a battery, the voltage oscillates in a sine wave pattern, varying with time as:

$V = V_0 \sin \omega t$

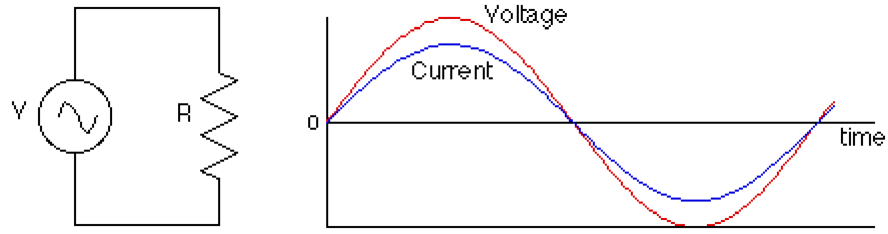
In a household circuit, the frequency is 60 Hz. The angular frequency is related to the frequency, f, by:

$\omega = 2 \pi f$

Vo represents the maximum voltage, which in a household circuit in North America is about 170 volts. We talk of a household voltage of 120 volts, though; this number is a kind of average value of the voltage. The particular averaging method used is something called root mean square (square the voltage to make everything positive, find the average, take the square root), or rms. Voltages and currents for AC circuits are generally expressed as rms values. For a sine wave, the relationship between the peak and the rms average is:

rms value = 0.707 peak value

Resistance in an AC circuit

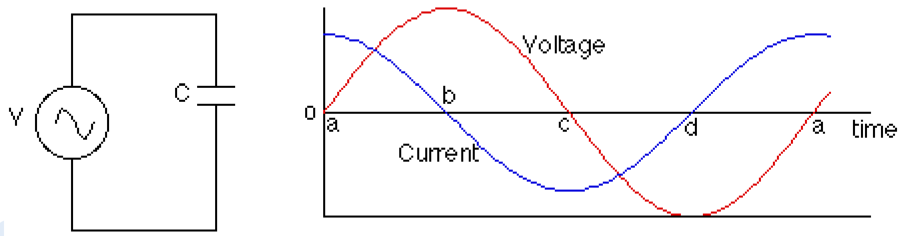


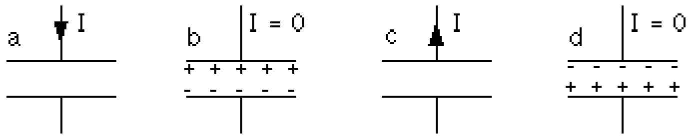
The relationship V = IR applies for resistors in an AC circuit, so

$I = V / R = (V_0 / R) \sin(\omega t) = I_0 \sin(\omega t)$

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:

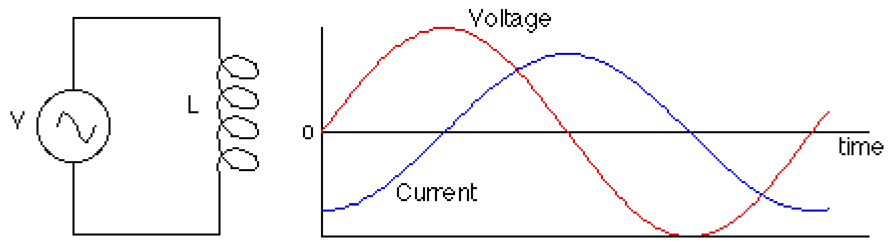
capacitive reactance: $X_C = 1 / \omega C = 1 / 2\pi fC$

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 : $\text{Energy} = 1/2\ CV^2$

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:

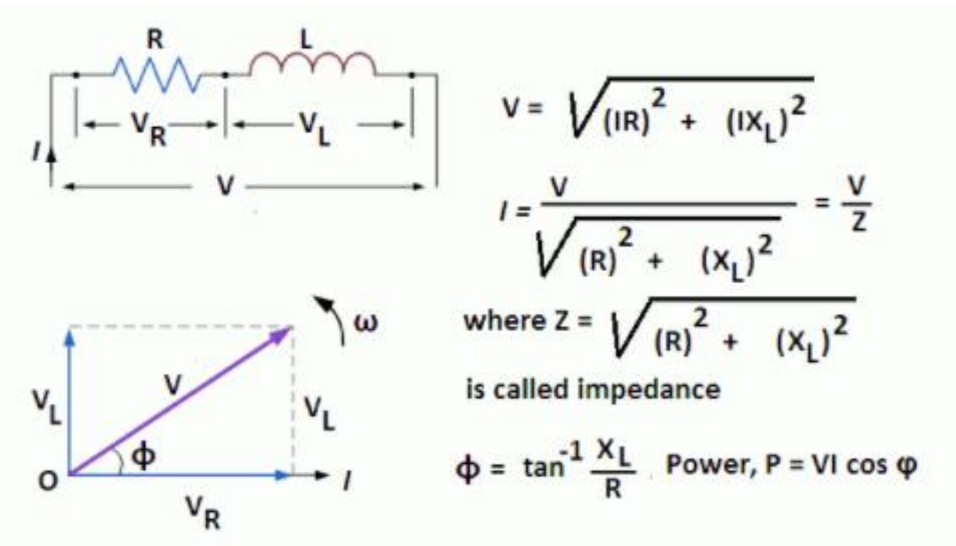
Energy density in a magnetic field = $B^2 / (2\ \mu_0)$

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:

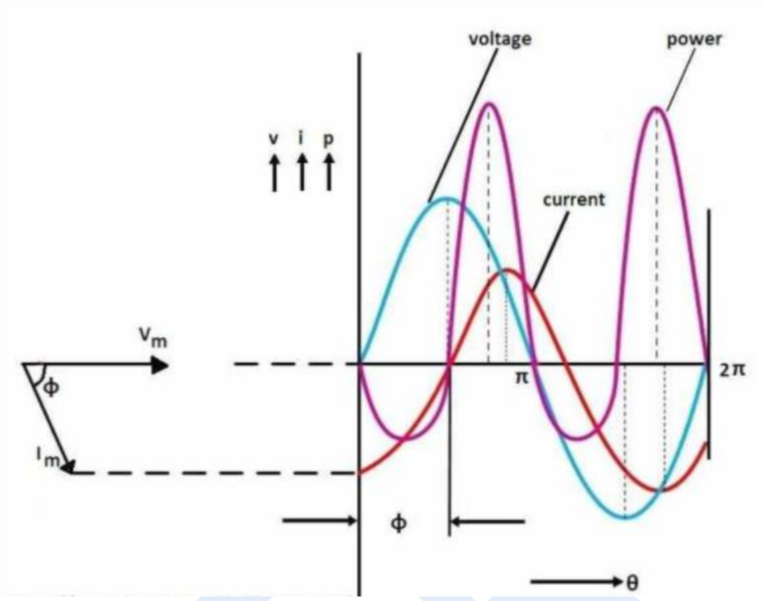
- RL series circuit
- RC series circuit
- RLC series circuit

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).

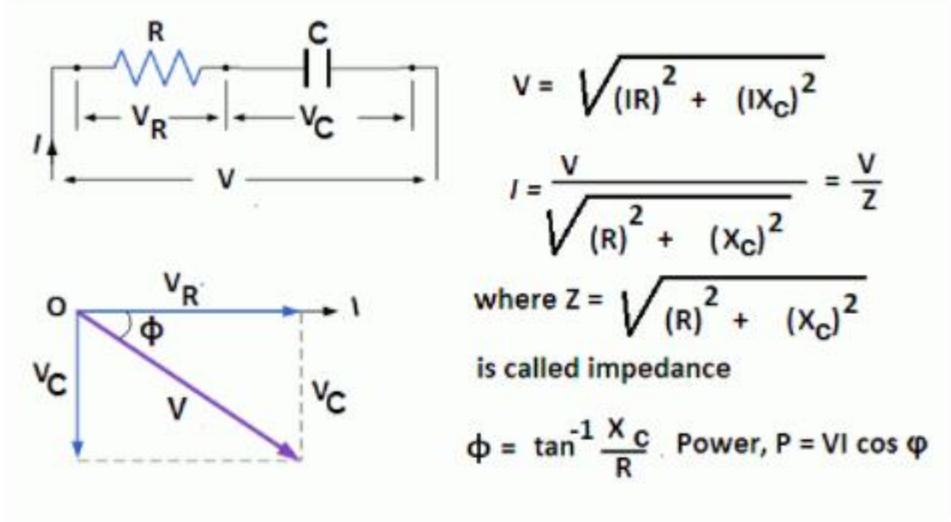


The power waveform for RL series circuit is shown in the figure. In this figure, voltage wave is considered as a reference. The points for the power waveform are obtained from the product of the corresponding instantaneous values of voltage and current.

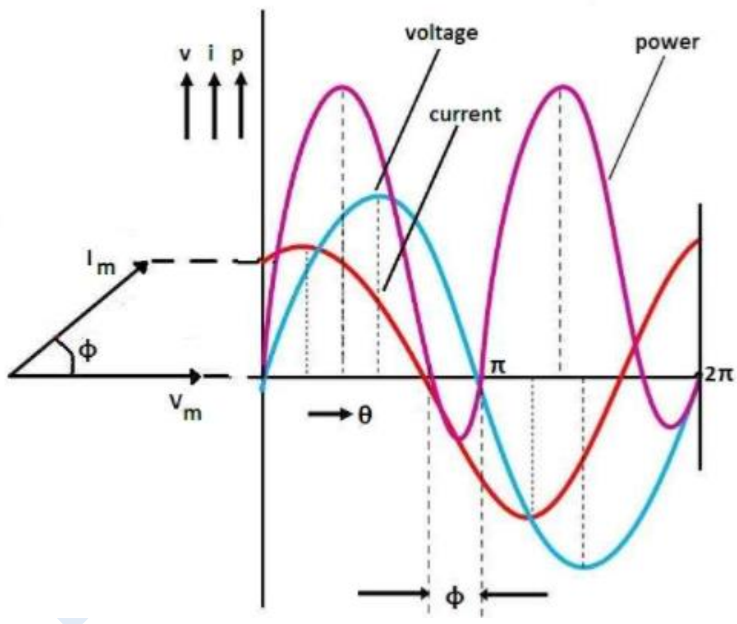
It is clear from the power waveform that power is negative between 0 and φ and between 180^o and $(180^o + φ)$. The power is positive during rest of the cycle.

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



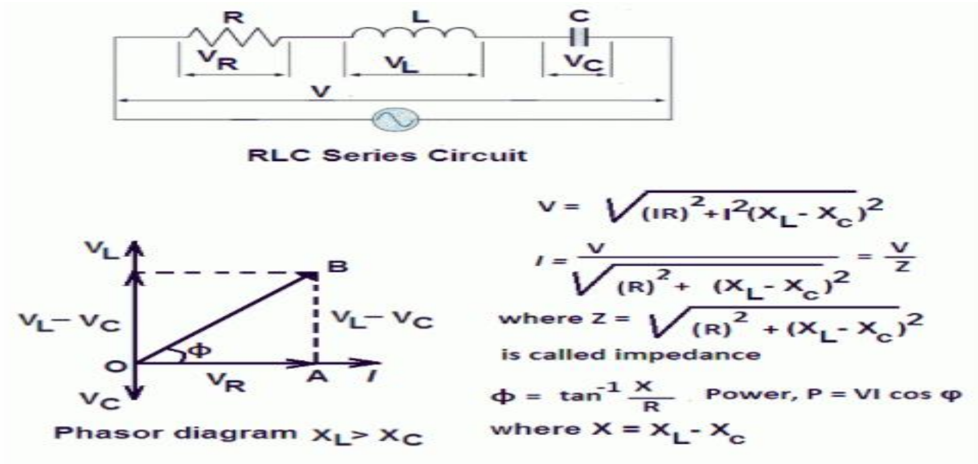
In an RC series circuit, a pure resistance (R) is connected in series with a pure capacitor (C). To draw the phasor diagram of RC series circuit, the current *I* (RMS value) is taken as reference vector. Voltage drop V_R is in phase with current vector, whereas, the voltage drop in capacitive reactance 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 $(180^o - \varphi)$ and 180^o and between $(360^o - \varphi)$ 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

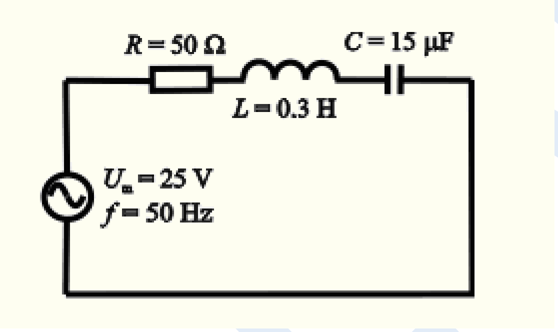
In AC circuit is composed of a serial connection of:

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.

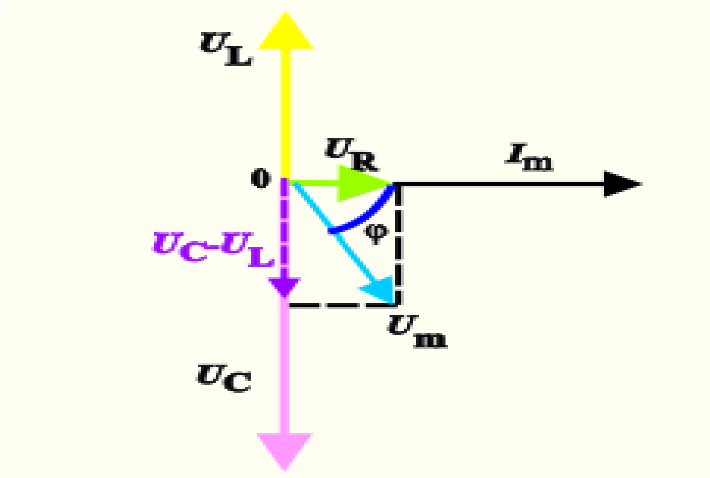
The voltage on the coil UL leads the current by π/2 (quarter of a period), therefore we draw its phasor pointing upwards – in the positive direction of the imaginary y-axis. We consider the fact that the phasors rotate in a counter clockwise direction. In the figure, this phasor is represented by yellow.

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

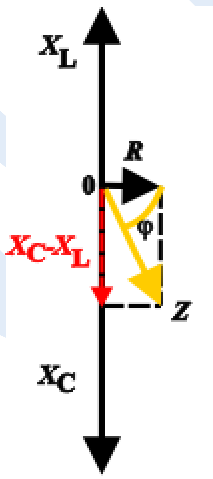
In the following figures the phasor diagrams are not illustrated by the same colour

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:

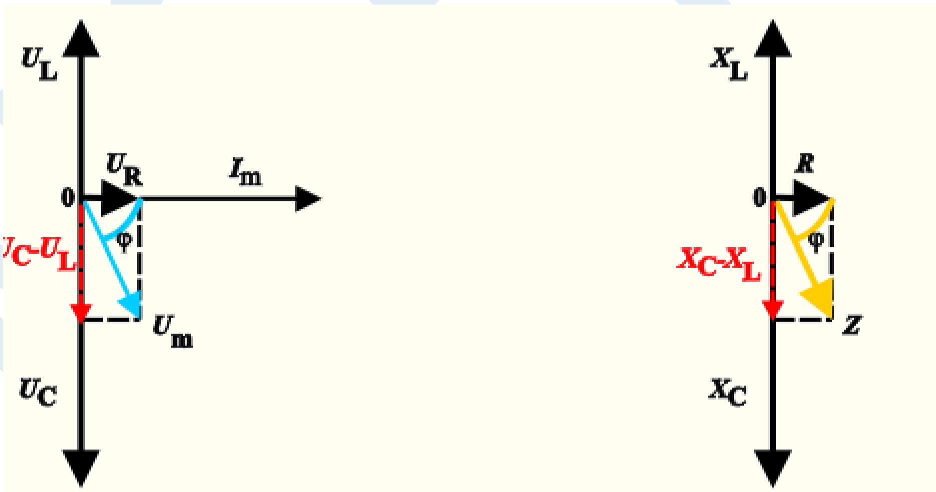
$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

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:

$$I_m = \frac{U_m}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} =$$

$$= \frac{25}{\sqrt{50^2 + \left(2\pi \cdot 50 \cdot 0.3 - \frac{1}{2\pi \cdot 50 \cdot 15 \cdot 10^{-6}}\right)^2}}\,\mathrm{A} \doteq 0.2\,\mathrm{A}$$

We can evaluate the **phase difference** by the impedance:

$$\operatorname{tg}\varphi = \frac{\omega L - \frac{1}{\omega C}}{R} = \frac{2\pi \cdot 50 \cdot 0.3 - \frac{1}{2\pi \cdot 50 \cdot 15 \cdot 10^{-6}}}{50} \doteq -2.4$$

Or it can be evaluated by using the voltage on individual components in the circuit:

The voltage on individual components of the circuit is:

$$U_R = I_m R \doteq 0.2 \cdot 50\,\mathrm{V} = 10\,\mathrm{V}$$

$$U_L = I_m \omega L \doteq 0.2 \cdot 2\pi \cdot 50 \cdot 0.3\,\mathrm{V} \doteq 18.85\,\mathrm{V}$$

$$U_C = \frac{I_m}{\omega C} \doteq \frac{0.2}{2\pi \cdot 50 \cdot 15 \cdot 10^{-6}}\,\mathrm{V} \doteq 42.44\,\mathrm{V}$$

We determine the size of the phase difference between the voltage and the current in the circuit from the phase diagram:

$$\operatorname{tg}\varphi = \frac{U_L - U_C}{U_R} \doteq \frac{18.85 - 42.44}{10} \doteq -2.4$$

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).

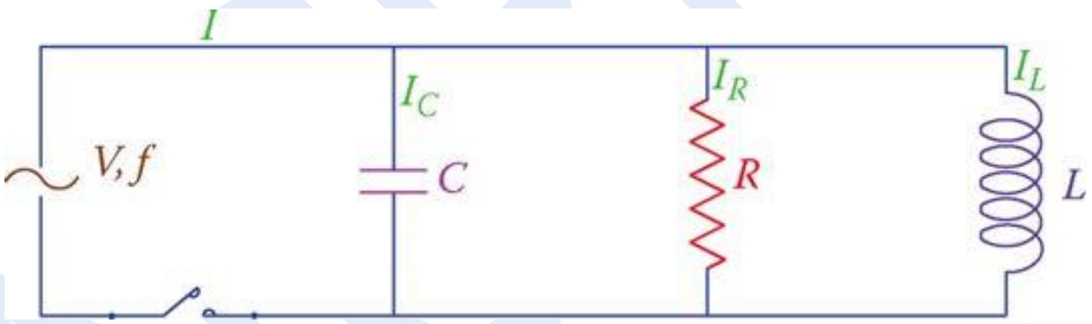
Parallel RLC Circuit

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

$$I = \sqrt{I_R^2 + (I_L - I_C)}^2 \qquad (1)$$

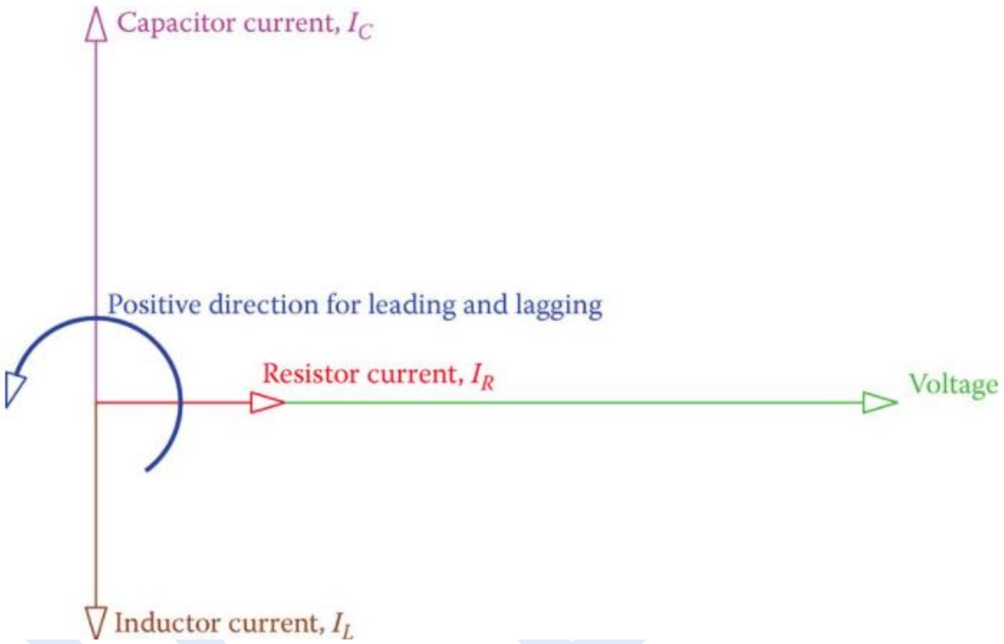


Figure 2 Vectors for the voltage and the three different currents in the *RLC* parallel circuit.

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.

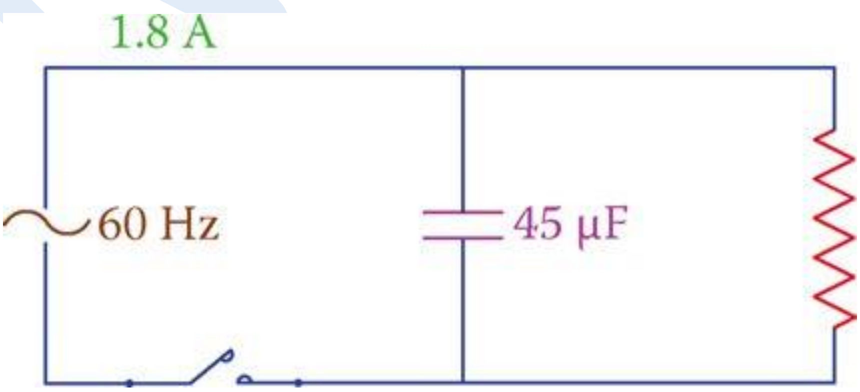


Figure 3 Circuit corresponding to **Example 1**.

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

$$\frac{V}{Z} = \sqrt{\left(\frac{V}{R}\right)^2 + \left(\frac{V}{X_L}\right)^2}$$

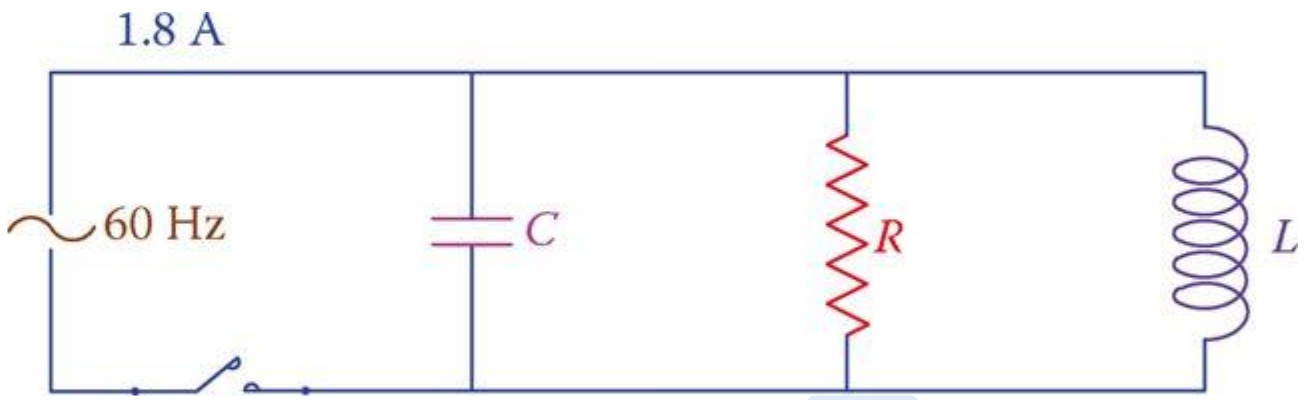
By omitting V from both sides the relationship between Z and R, L, and C can be found then as

$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2} \qquad (2)$$

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

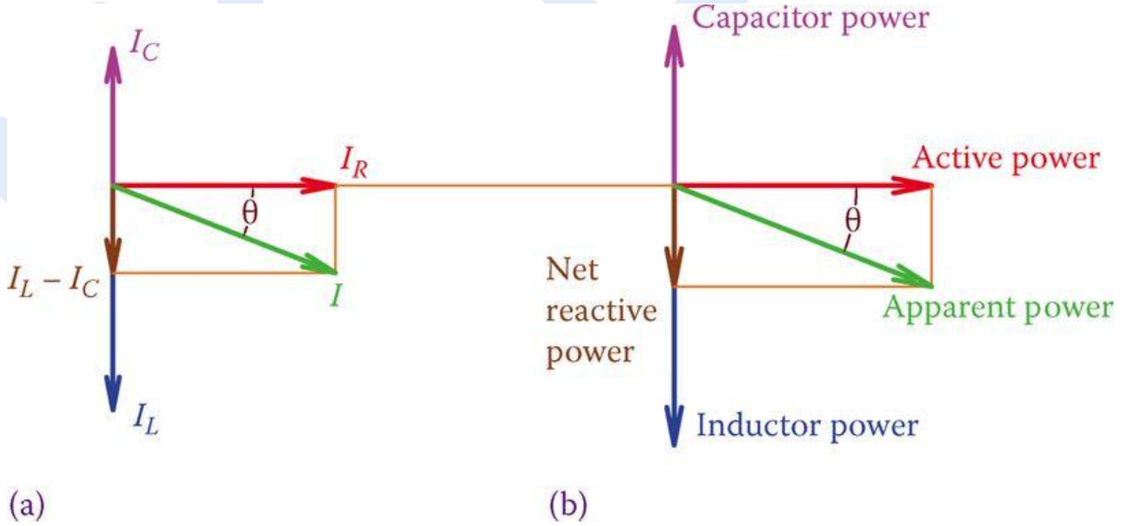
In the circuit shown in **Figure 4**, $R = 55\ \Omega$, $L = 0.08$ H, and $C = 1\ \mu$F, find the impedance of the circuit and the applied voltage.



$$X_L = 2 * 3.14 * 60 * 0.08 = 30.16\Omega$$
$$X_C = \frac{1}{2 * 3.14 * 60 * 0.000001} = 26.5\Omega$$
$$\frac{1}{Z} = \sqrt{\left(\frac{1}{55}\right)^2 + \left(\frac{1}{55} - \frac{1}{26.5}\right)^2} = \frac{1}{53.33}$$
$$Z = 53.33\Omega$$

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

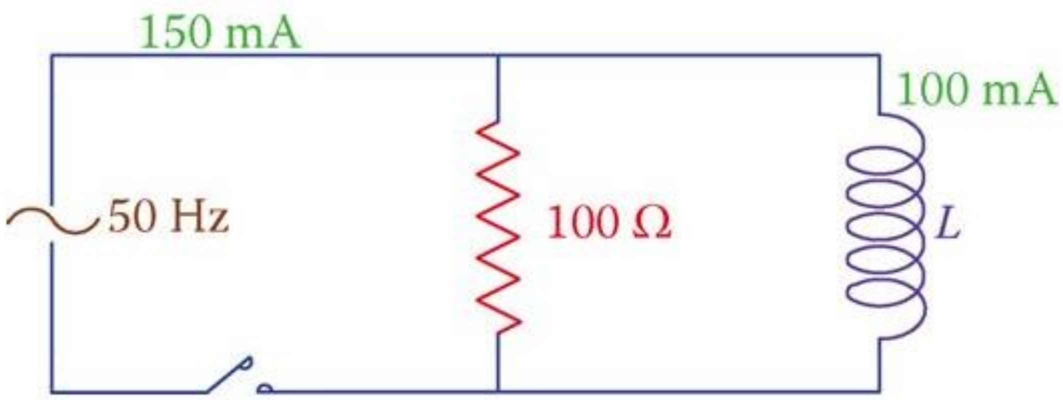
Figure 5 shows a lagging circuit. In practice, most of the circuits are lagging because of the presence of electric motors, unless the effects of electric motors are compensated by inserting capacitors that introduce capacitive power to a circuit (see power factor correction). The power factor in a parallel *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.

SERIES AND PARALLEL RESONANCE

This page on Series resonance vs parallel resonance describes **difference between** Series resonance and parallel resonance. It also mentions what is resonance condition in electronic circuit.

When alternating voltage is applied to a circuit which contains capacitor and coil, response of the circuit is maximum when applied voltage frequency is equal to natural frequency of the circuit. The form of electrical response depends on whether the capacitor(C) and inductor coil (L) are connected in series or parallel.

If the components are connected in series as shown in figure-1, the condition is referred as **series resonance** and circuit is known as series resonant circuit. If the components are connected in parallel as shown in figure-2, the condition is referred as **parallel resonance** and circuit is known as parallel resonant circuit.

In other words:
In AC circuits, a condition in which inductive reactance becomes exactly equal to capacitive reactance is referred as resonance.

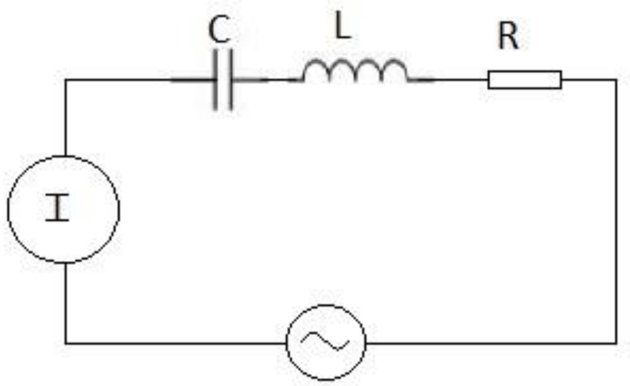
XL = XC
➨ $2*\pi f*L = [\ 1/\{\ (2*\pi)*\ (f*C)^{0.5}\ \}\ ]$
➨ $Z = \{\ R^2 + (\ XL - XC\ )^2\ \}^{0.5}$

Resonance Frequency

In a circuit consisting of L and C components, the frequency at which resonance occurs is called **resonance frequency**.

➨ $Fr = 1\ /\ \{\ (2*\pi)*(L*C)^{0.5}\ \}$
Where,
Fr = resonant frequency or resonance frequency
L = Inductance in henrys
C = Capacitance in Farads

Series resonant circuit



Series Resonance Circuit

A series L-C circuit in which magnitudes of capacitive and inductive reactances are exactly equal is known as series resonant circuit as mentioned above. It is also known as acceptor circuit.

Characteristics of series resonance circuit:
• Minimum impedance
• Maximum circuit current
• cos(φ) = 1 , hence current and voltage becomes in phase.
• Circuit current becomes proportional to circuit resistance i.e. I ~ 1/R

Uses of series resonance circuit:
• As frequency selection circuit in radio and TV tuner circuits.
• As band pass filter circuit.

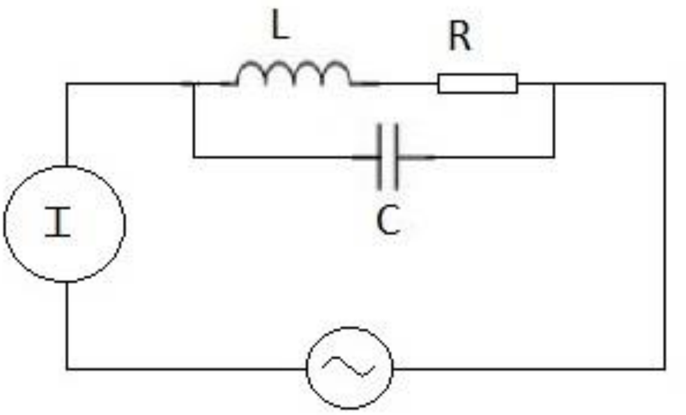
Circuit Q or Q factor

Ratio of inductive reactance to the resistance is called **circuit-Q**. It is known as magnification factor.
➨ Q = XL/R
Where,
Q = circuit-Q, unitless
XL = inductive reactance, Ohm
R = circuit resistance, Ohm
Selectivity is proportional to Q.

Bandwidth of Resonance Curve

F2-F1 = R/(2*π*L)
Where,
F2 = Upper frequency of bandwidth (Hertz)
F1 =Lower frequency of bandwidth (Hertz)
R = circuit resistance, Ohm
L = Inductance , Henrys

parallel resonant circuit



Parallel Resonance Circuit

A parallel L-C circuit in which magnitudes of capacitive and inductive reactances are exactly equal is known as parallel resonant circuit as mentioned above. It is also known as rejector circuit.

Characteristics of parallel resonance circuit:
• Maximum impedance
• Minimum circuit current
• cos(φ) = 1, hence voltage and current becomes in phase
• Circuit current depends on circuit impedance, Z = L/C or I ~ -(1/R)

Uses of parallel resonance circuit:
• As a Band Stop Filter
• As a tank circuit in Oscillators
• As a plate load in IF and RF amplifiers
• As I.F. trap in aerial circuit of radio as well as TV receivers.

Following table mention comparison between series resonance circuit and parallel resonance circuit.

Specifications	**Series resonance circuit**	**Parallel resonance circuit**
Impedance at resonance	Manimum	Maximum
Current at resonance	Maximum	Minimum

Effective impedance	R	L/CR
Resonant frequency	$1/(2*\pi*(LC)^{0.5})$	$(1/2*\pi)*\{(1/LC)- R^2/L^2\}^{0.5}$
It magnifies	Voltage	Current
It is known as	Acceptor circuit	Rejector circuit
Power Factor	Unity	Unity

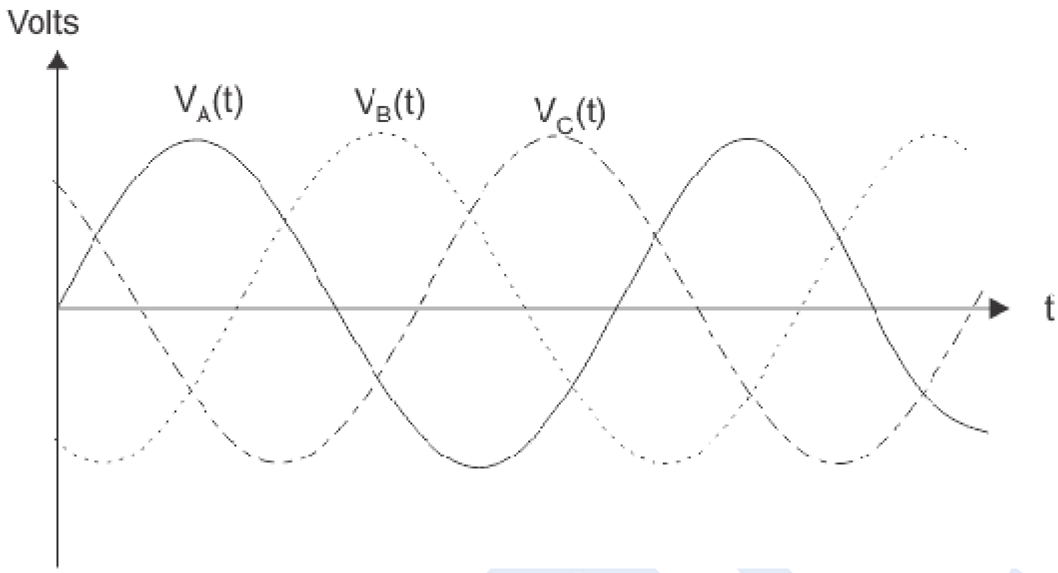
This difference between acceptor and rejector circuit is useful to understand comparison between the both.

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.

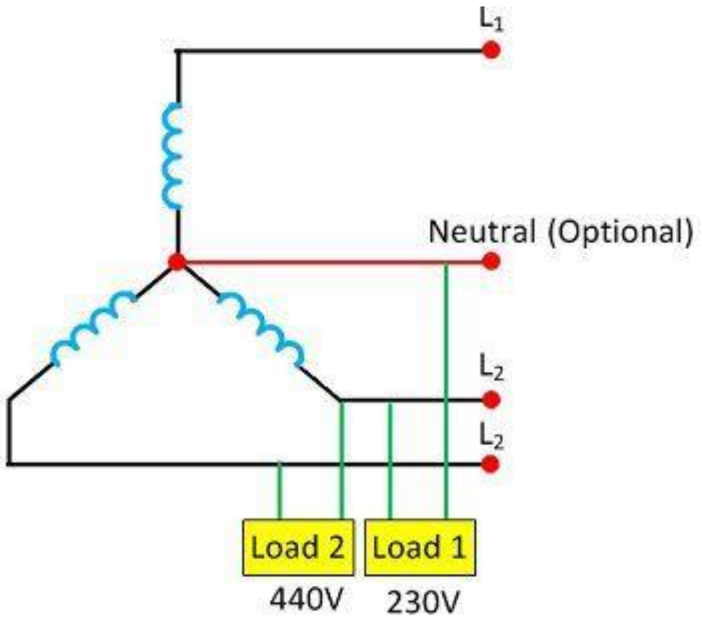
Till now we can say that there are three voltage source connected together to form a three phase circuit and actually it is inside the generator. The generator is having three voltage sources which are acting together in 120^o phase difference. If we can arrange three single phase circuit with 120^o 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:

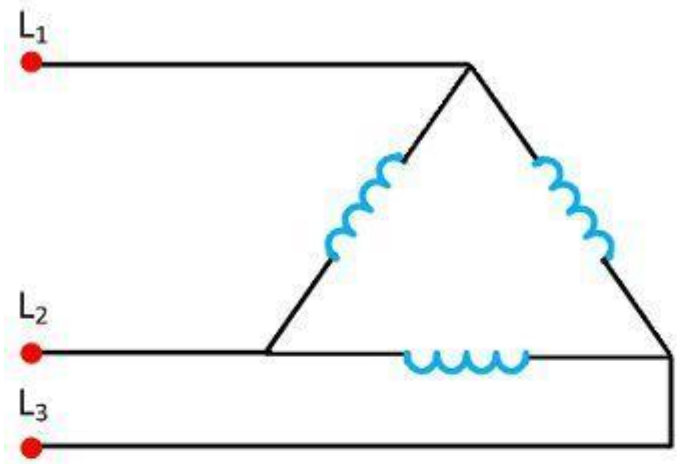
$$E_{line} = \sqrt{3}\ E_{phase}$$

$$I_{line} = I_{phase}$$

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.

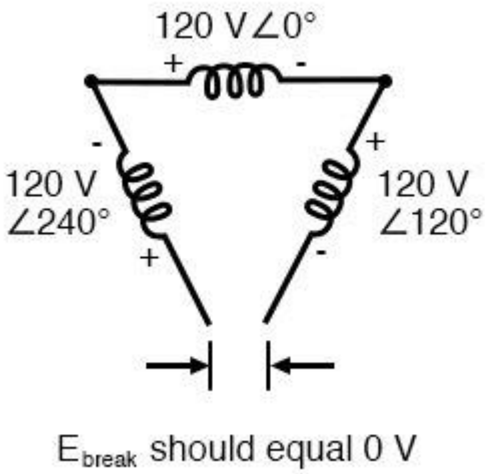
Starting with the top winding and progressing counter-clockwise, our KVL expression looks something like this:

$$(120\text{ V}\angle 0°) + (120\text{ V}\angle 240°) + (120\text{ V}\angle 120°)$$

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)



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:

$$(120\text{ V}\angle 120°) + (120\text{ V}\angle 0°) + (120\text{ V}\angle 240°) + E_{break} = 0$$

$$0 + E_{break} = 0$$

$$E_{break} = 0$$

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:

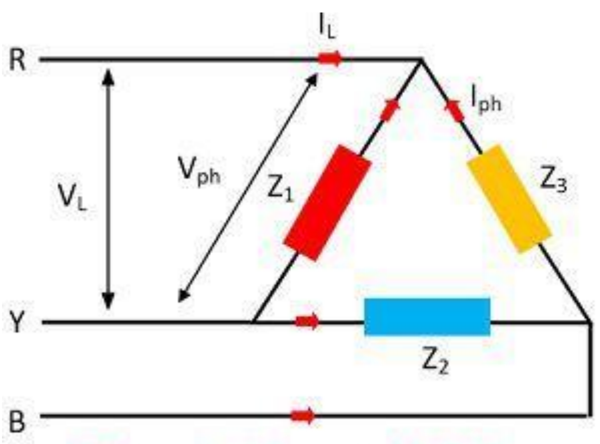
For Δ ("delta") circuits:

$$E_{line} = E_{phase}$$

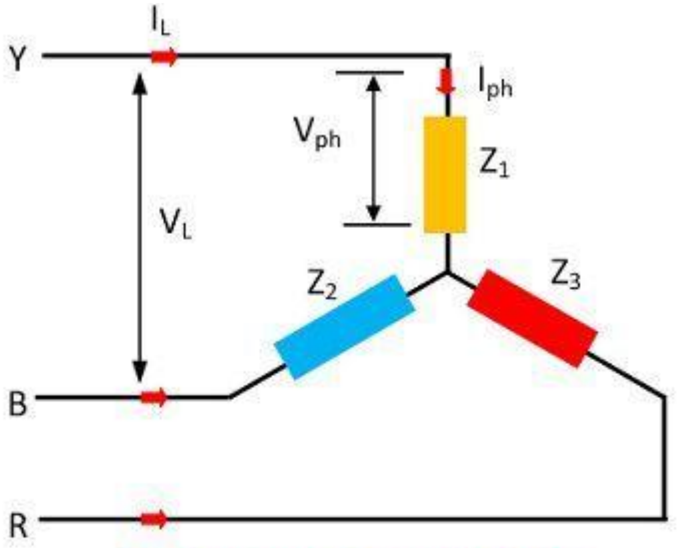
$$I_{line} = \sqrt{3}\ I_{phase}$$

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

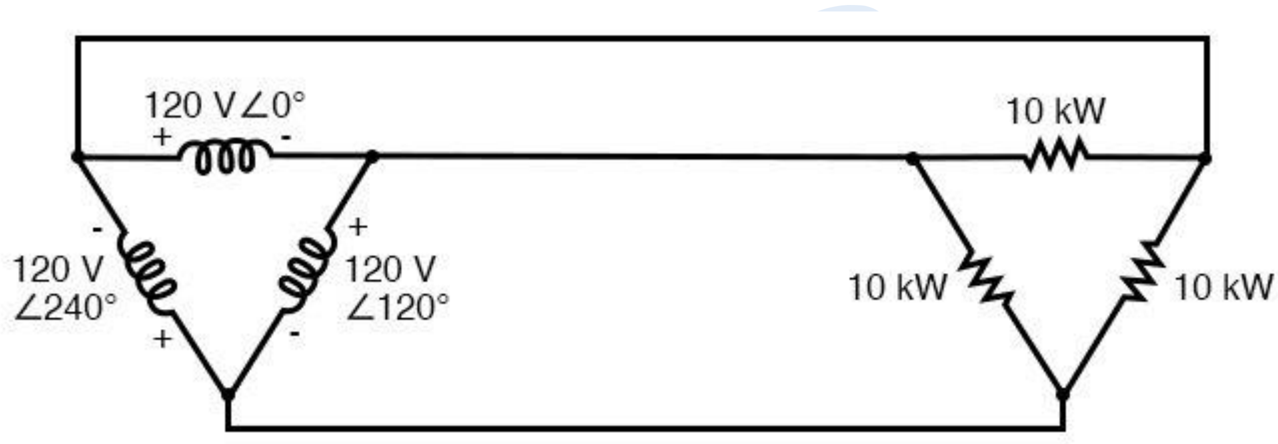


3 - Phase Load Connected in Star

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).

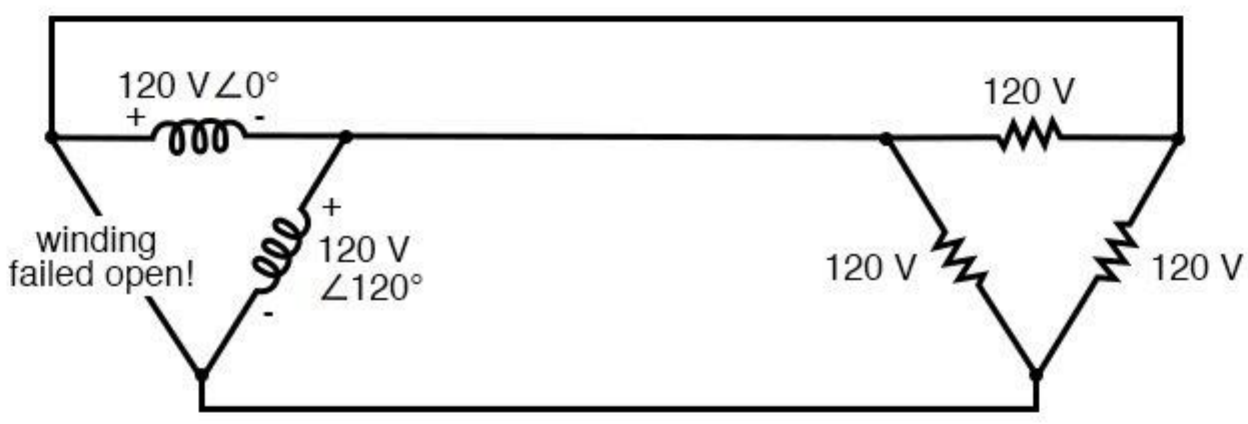
One distinct advantage of a Δ-connected system is its lack of a neutral wire. With a Y-connected system, a neutral wire was needed in case one of the phase loads were to fail open (or be turned off), in order to keep the phase voltages at the load from changing.

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.

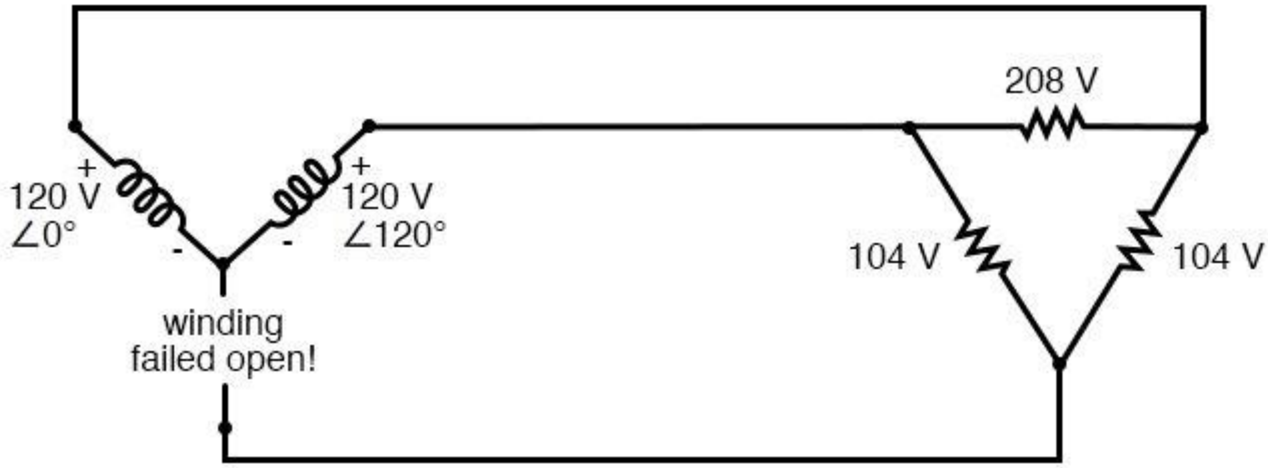
Perhaps the greatest advantage of the Δ-connected source is its fault tolerance.

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!



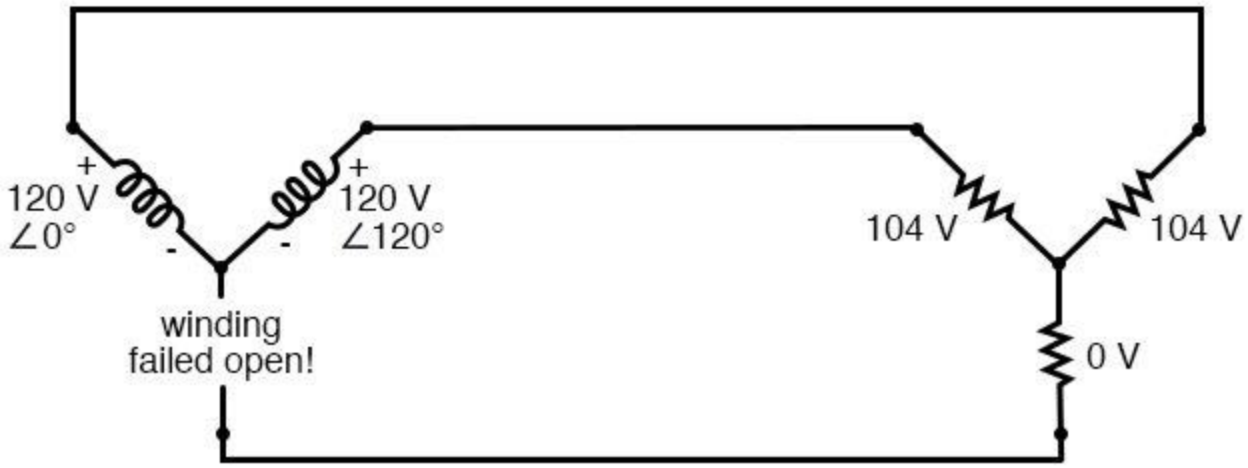
Even with a source winding failure, the line voltage is still 120 V, and the load phase voltage is still 120 V. The only difference is extra current in the remaining functional source windings.

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:

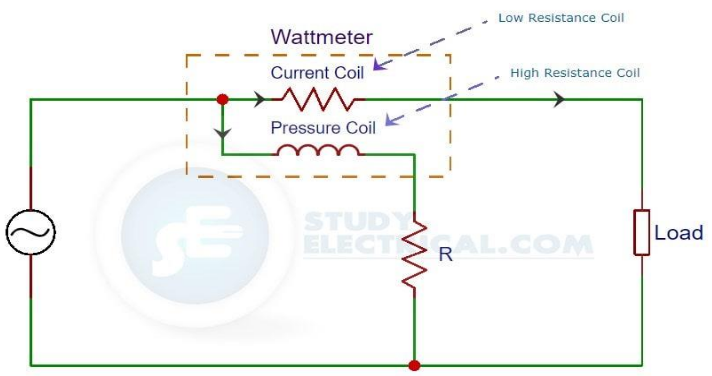
1. Three wattmeters method
2. Two wattmeters method
3. Single wattmeter method.

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

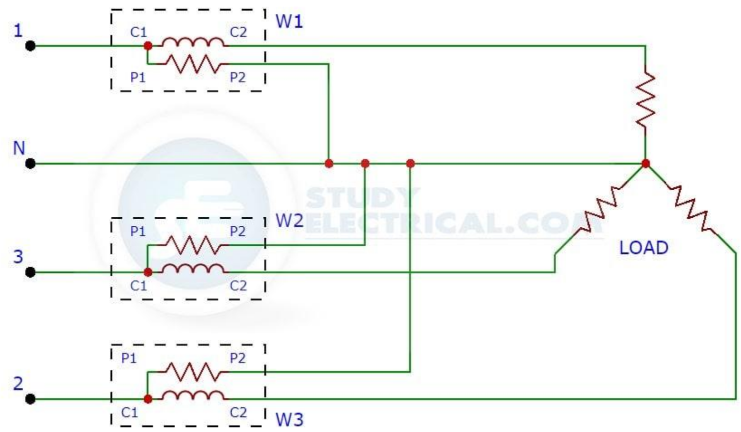
Let us discuss one by one each method in detail.

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.

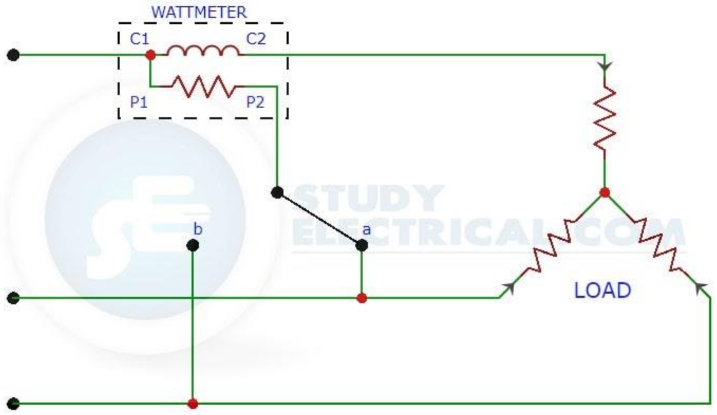
To measure power it is not necessary to use three wattmeter, even two wattmeters can be used for the purpose.

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.

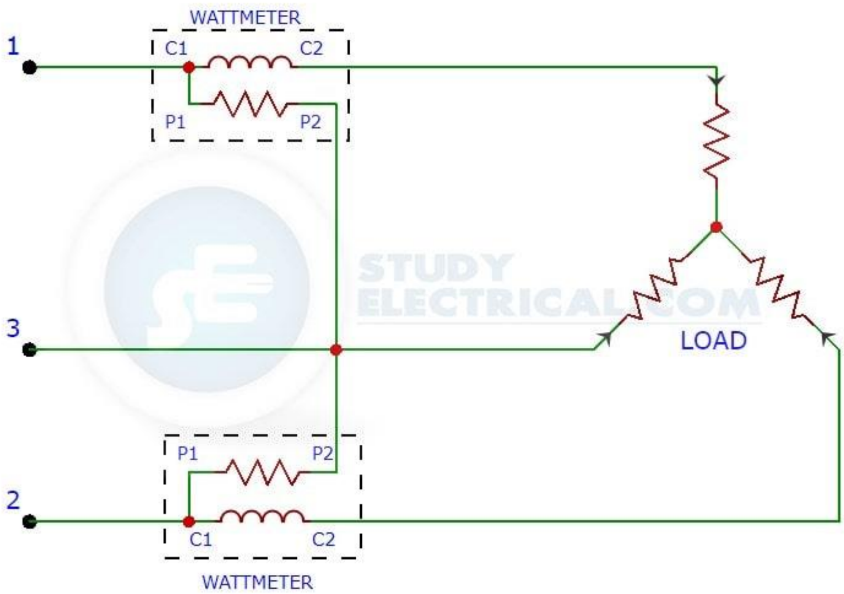
Two Wattmeter Method

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 VL = 400 V,

line current, IL = 8.6A and

power, $P = \sqrt{3}\ V_L I_L \cos\varphi$

Hence

power factor = $\cos\varphi = P\ \sqrt{3}\ V_L I_L$

= 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 $\varphi = \tan^{-1} 1\ \sqrt{3}$ $=30^\circ$

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 P_1 and P_2 respectively

Then $P_1 + P_2$ = 12kW ---(1)

$\tan\varphi = \sqrt{3}(P_1 - P_2)/(P_1 + P_2)$

And power factor=0.6= cos φ.

Angle φ= cos−10.6=53.13◦ and

tan 53.13◦ =1.3333.

Hence

1.3333 =√3(P1 − P2)/12

From which,

P1 − P2 = 12(1.3333) /√3

i.e. P1 −P2 =9.237kW ----(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)=1.38kW

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, VL

(a) For a star connection, VL =√3Vp Hence phase voltage, Vp = VL/√3

= 415 /√3

= **239.6 V or 240 V**

correct to 3 significant figures

(b) Phase current, Ip = Vp/Rp

= 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,

$P = \sqrt{3}\, V_L I_L \cos\varphi = \sqrt{3}\,(415)(14.50)(0.6042)$ = **6.3kW** (Alternatively,

$P = 3I^2R = 3(14.50)^2(10) =$ **6.3kW**)

(b) **Delta connection**

$V_L = V_p = 415$ V,

$Z_p = 16.55$_, $\cos\varphi = 0.6042$ lagging (from above). Phase current,

$I_p = V_p/Z_p = 415/16.55 = 25.08$A. Line current,

$I_L = \sqrt{3} I_p = \sqrt{3}(25.08) = 43.44$A.

Power dissipated,

$P = \sqrt{3}\, V_L I_L \cos\varphi$

$= \sqrt{3}\,(415)(43.44)(0.6042)$ = **18.87kW**

(Alternatively,

$P = 3I^2R$

$= 3(25.08)^2(10)$ = **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, $I_p = V_p/Z_p$

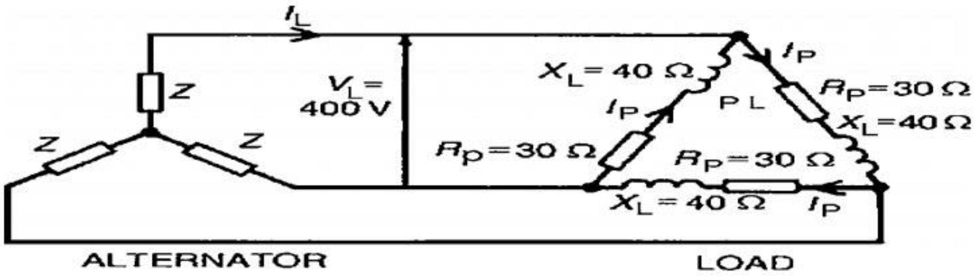
$V_p = V_L$ for a delta connection,

Hence V_p =400V.

Phase impedance,

$Z_p = \sqrt{(R^2 + X_L^2)}$

$= \sqrt{(30^2 + 40^2)} = 50$



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

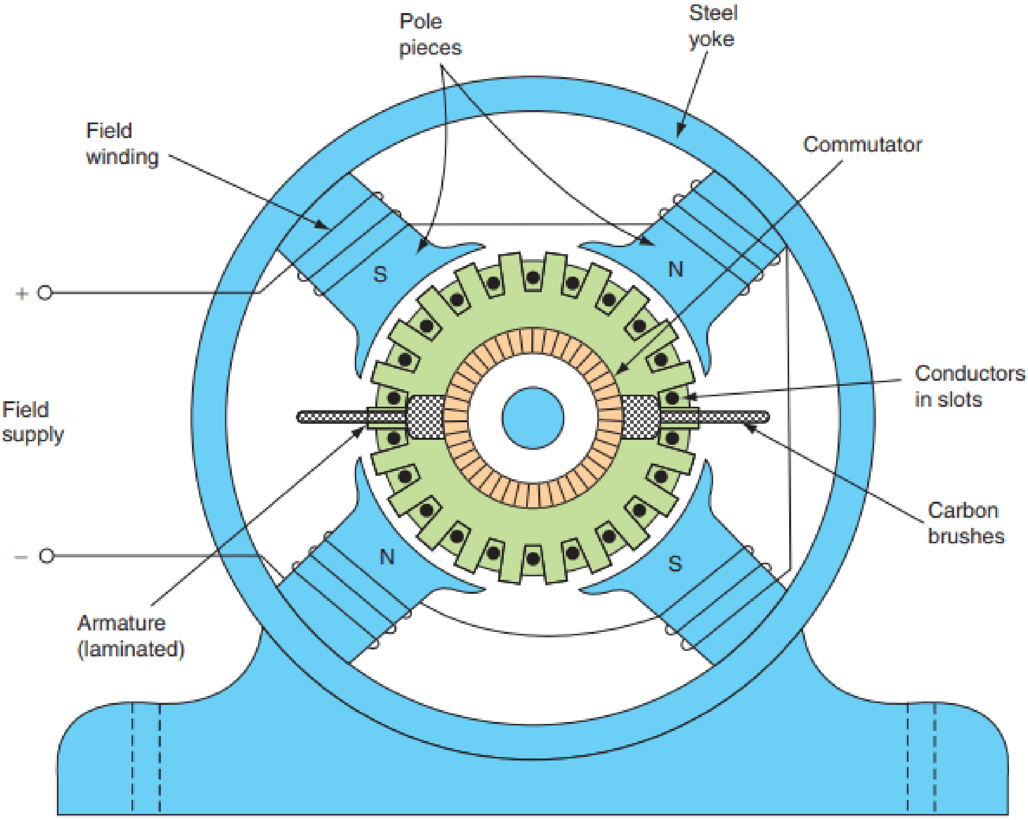
DC MACHINES

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.

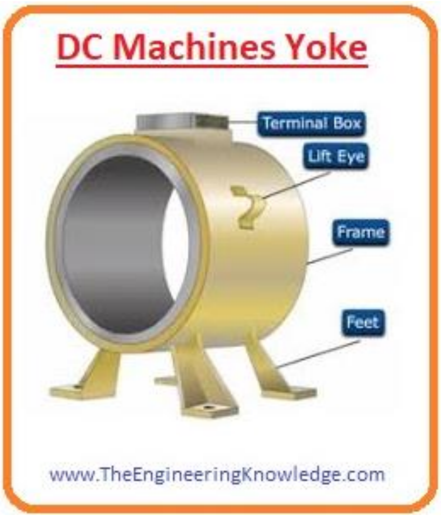
DC MACHINES CONSTRUCTION

- 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

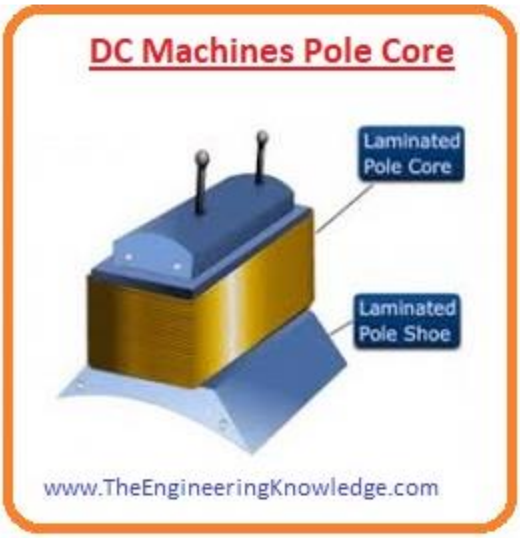
- The yoke of machines is also known as the frame, the main working of this part is to provide protection to the internal circuitry of a machine from the outer environment, temperature, moisture, and some other factors.
- This part of the machine is constructed with the cast steel and cast iron.



DC Machines Pole Core

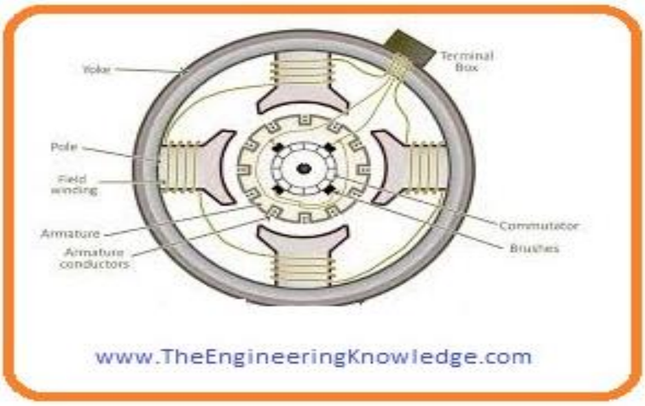
- At stator of the dc machines, the poles are of an electromagnet the windings on these poles are known as the field windings.
- The input provided at the stator connected with the field windings generate flux at the stator and make poles electromagnet.

These poles are constructed with cast steel, cast iron.



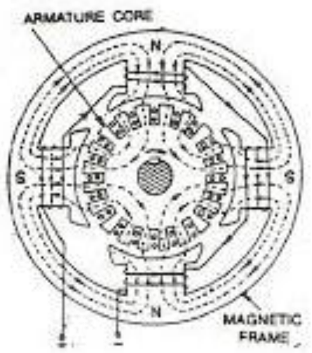
DC Machines Field Windings

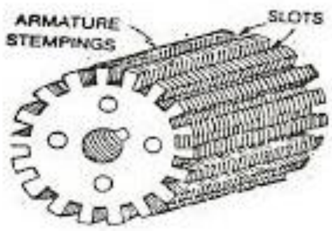
- These windings are wound at the sating part of machines on the poles at the stator. These windings are constructed with copper. The current provided at these windings generates flux and makes poles electromagnet.

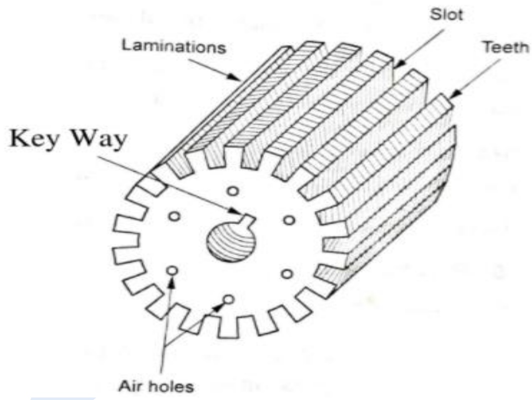


DC Machines Armature Core

- 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

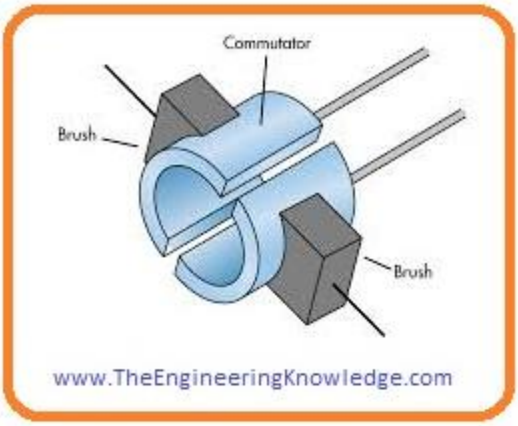
- The windings wound on the rotor if the dc machine is known as the armature windings. When the rotor rotates due to flux linking of stator the voltage induced in this part of machines.
- These windings are constructed with copper like the stator windings.

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.

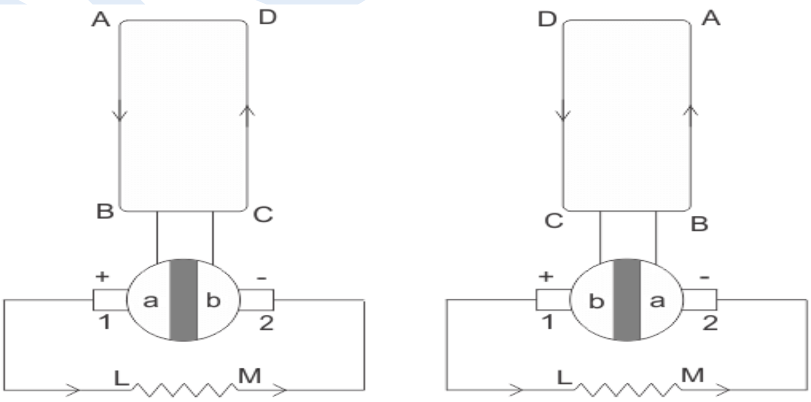


DC GENERATORS

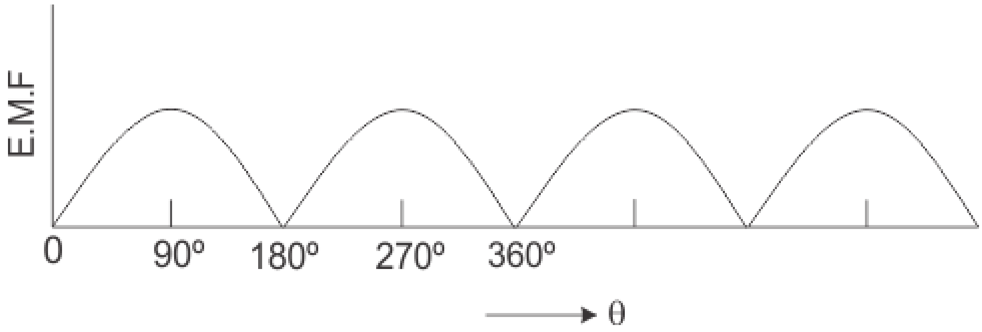
What is a DC Generator?

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:

$$E = \frac{P\varphi N}{60} \text{ x } \frac{Z}{A} = \frac{PZ\varphi N}{60\ A} \quad \text{volts} \quad \text{or}$$

$$E = \frac{PZ\varphi n}{A} \quad \ldots\ldots.(5)$$

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 (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

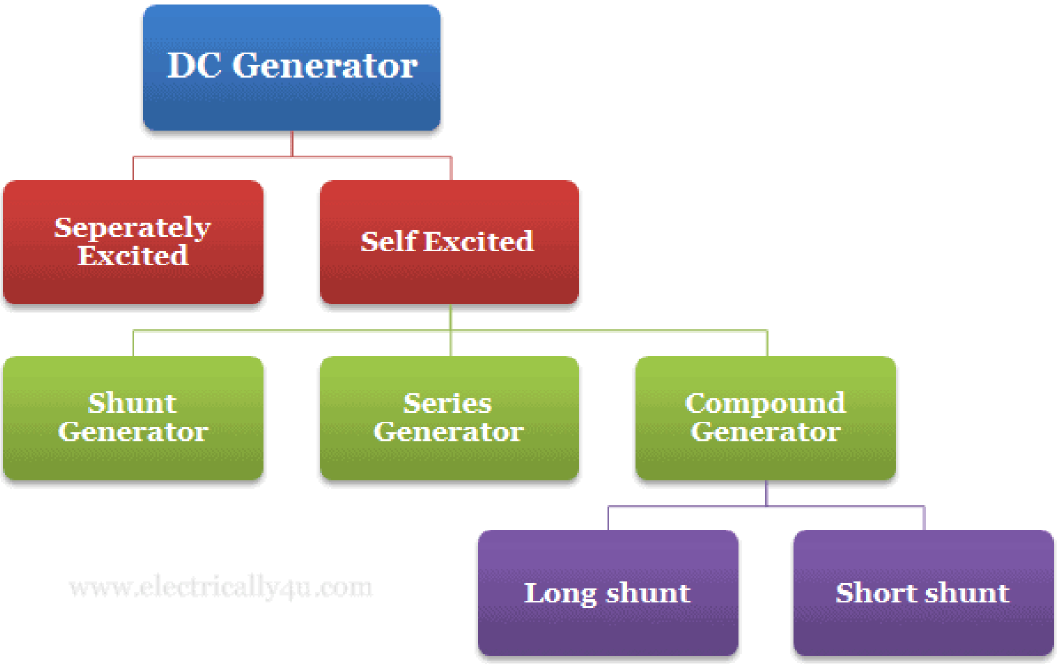
Here, number of parallel paths is equal to number of conductors in one path i.e. P = A

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

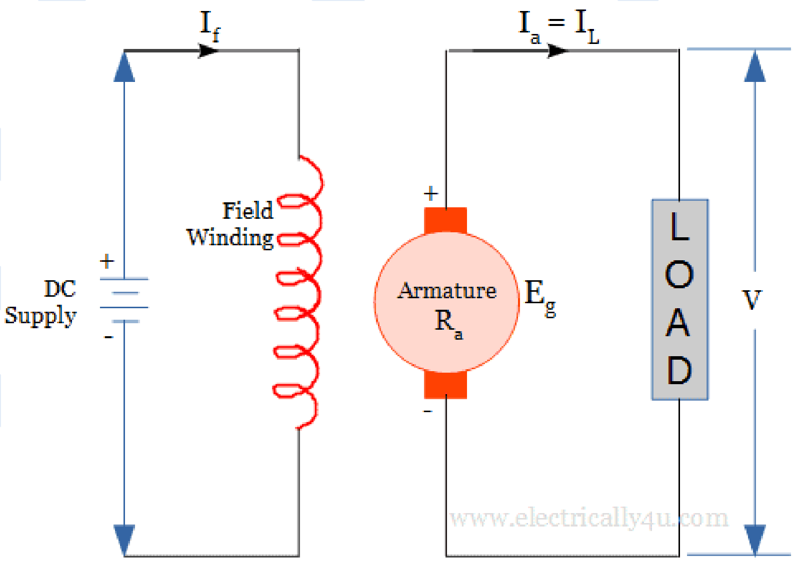
DC generators are classified based on the way in which the field windings are excited. The different types of DC generator are shown below



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.

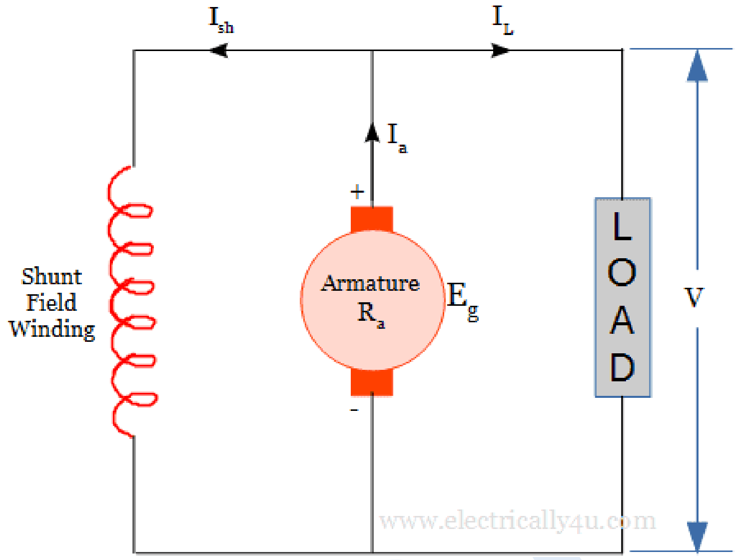
There are three types of self-excited DC generator based on the way, in which the field coils and armature are connected. They are

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, $V = E_g – I_a R_a – V_{br}$

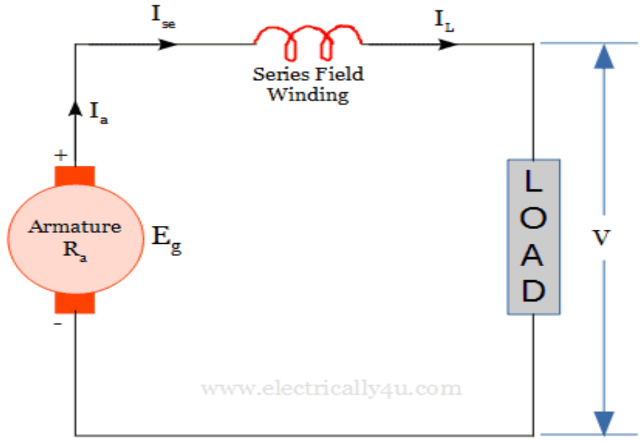
Power developed in the DC generator = $E_g I_a$

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

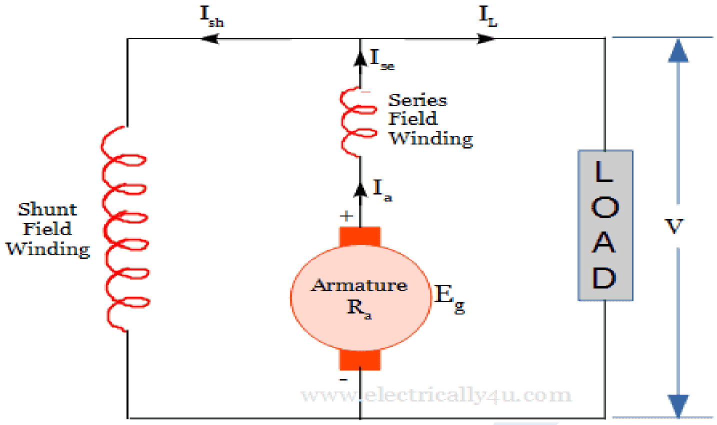
DC compound generator has both shunt field winding and series field winding. One field winding is connected in series with the armature and another field winding is connected in parallel with the armature.

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

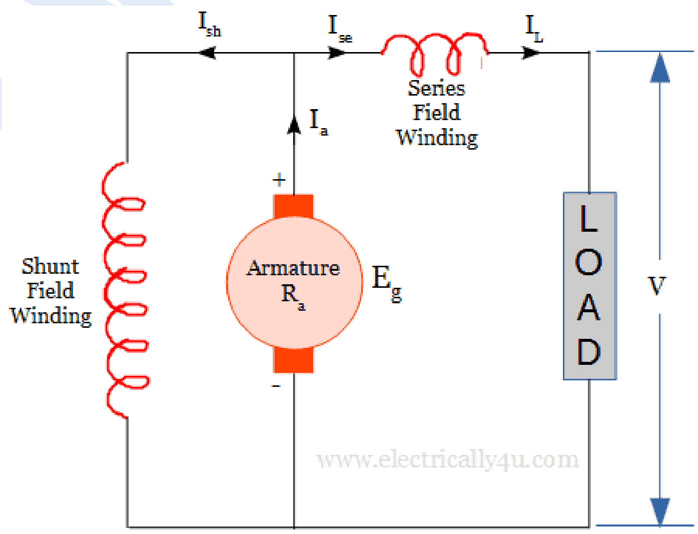
Terminal voltage equation is given by, $V = E_g – I_a R_a – I_a R_{se} – V_{br}$

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

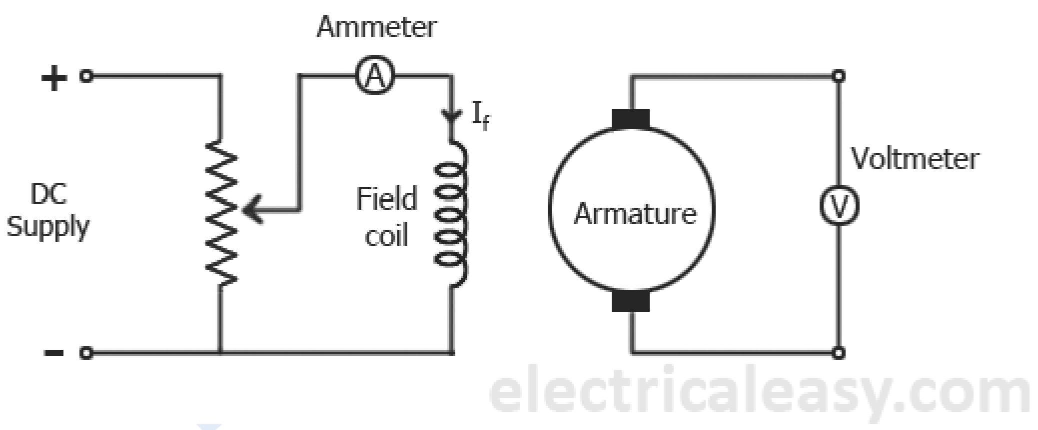
CHARACTERISTICS OF DC GENERATORS

Generally, following three characteristics of DC generators are taken into considerations: (i) Open Circuit Characteristic (O.C.C.), (ii) Internal or Total Characteristic and (iii) External Characteristic.

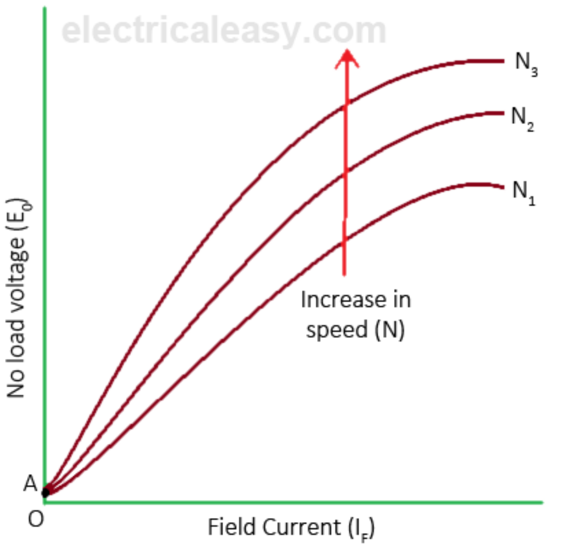
These **characteristics of DC generators** are explained below.

1. OPEN CIRCUIT CHARACTERISTIC (O.C.C.) (E_0/I_F)

Open circuit characteristic is also known as **magnetic characteristic** or **no-load saturation characteristic**. This characteristic shows the relation between generated emf at no load (E_0) and the field current (I_f) at a given fixed speed. The O.C.C. curve is just the magnetization curve and it is practically similar for all type of generators. The data for O.C.C. curve is obtained by operating the generator at no load and keeping a constant speed. Field current is gradually increased and the corresponding terminal voltage is recorded. The connection arrangement to obtain O.C.C. curve is as shown in the figure below. For shunt or series excited generators, the field winding is disconnected from the machine and connected across an external supply.



Now, from the emf equation of dc generator, we know that Eg = kϕ. Hence, the generated emf should be directly proportional to field flux (and hence, also directly proportional to the field current). However, even when the field current is zero, some amount of emf is generated (represented by OA in the figure below). This initially induced emf is due to the fact that there exists some residual magnetism in the field poles. Due to the residual magnetism, a small initial emf is induced in the armature. This initially induced emf aids the existing residual flux, and hence, increasing the overall field flux. This consequently increases the induced emf. Thus, O.C.C. follows a straight line. However, as the flux density increases, the poles get saturated and the ϕ becomes practically constant. Thus, even we increase the I_f further, ϕ remains constant and hence, Eg also remains constant. Hence, the O.C.C. curve looks like the B-H characteristic.



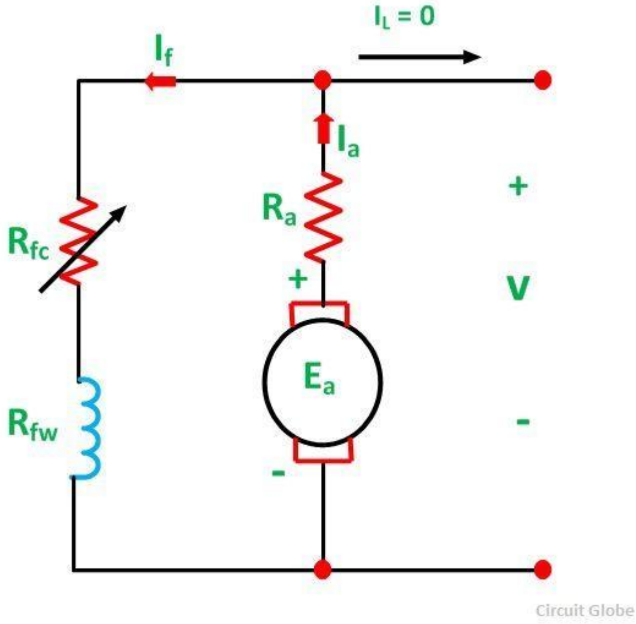
Open Circuit Characteristic (O.C.C.)

The above figure shows a typical no-load saturation curve or open circuit characteristics for all types of DC generators.

Voltage Buildup in Self Excited Generator or Shunt DC Generator

A **self-excited generator** is also known as DC Shunt Generator, as the field winding is connected in parallel with the armature. Thus, the armature voltage supplies the field current. This type of generator supplies its own field excitation.

The equivalent circuit of a shunt DC Generator is shown in the figure below:



Equivalent Circuit of a Shunt DC Generator

Considering the above figure let us assume that the generator is working at no-load condition, and the prime mover drives the armature at a certain speed. This generator will build up the desired terminal voltage. The residual flux present in the field poles of the DC generator is responsible for the voltage buildup. A small voltage Ear is generated and is given by the equation shown below.

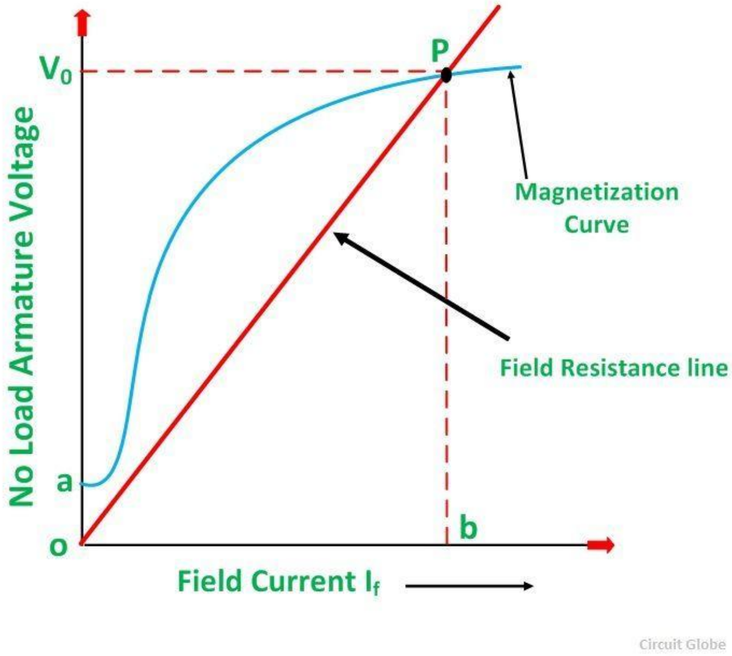
$$E_{ar} = K\varphi_{res}\omega$$

This voltage is of the order of 1 to 2 volts. This voltage causes a current If to flow in the field winding of the generator. The field current is given by the equation.

$$I_f = \frac{V}{R_f}$$

The flux is increased by a magnetomotive force produced by the field current. As a result, of this, the generated voltage Ea increases. This increased armature voltage increases the terminal voltage. With the increase in the terminal voltage, the field current If increases further. This, in turn, increases flux and hence the armature voltage is further increases, and the process of voltage buildup continues.

The voltage buildup curve of a DC shunt generator is shown below:



Voltage Buildup of a DC Shunt Generator

The generator is on no load during the process of voltage buildup, thus, the following equations shown below give the steady-state operation.

$$I_a = I_f$$

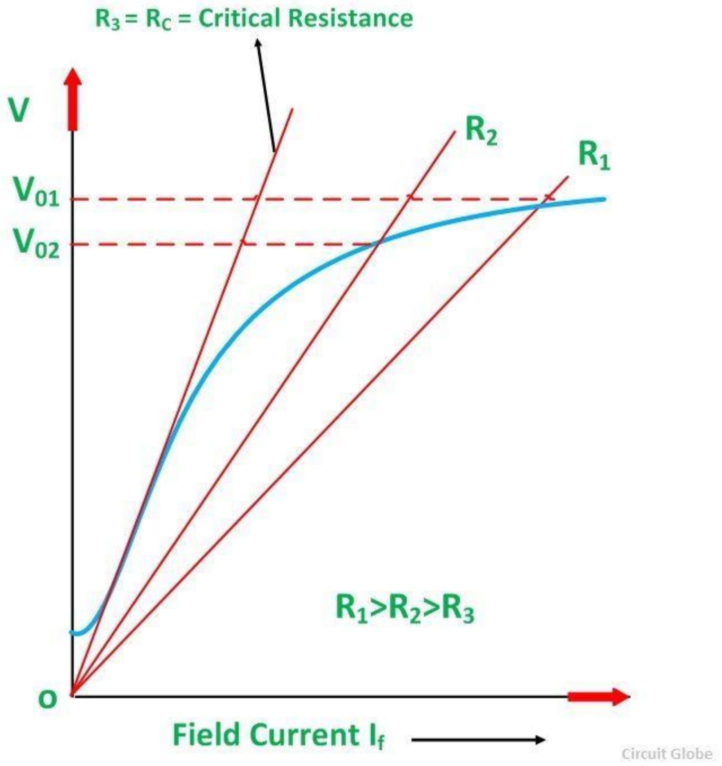
$$V = E_a - I_a R_a = E_a - I_f R_a \dots\dots\dots.(1)$$

Since the field current If in a shunt generator is very small, the voltage drop $I_f R_a$ can be neglected. Thus, equation (1) becomes:

$$V = E_a \quad \dots\dots..(2)$$

The straight line given by V= $I_f R_f$ shown in the above figure is known as **Field Resistance Line.**

The voltage buildup in the DC shunt generator for various circuit resistances is shown below:

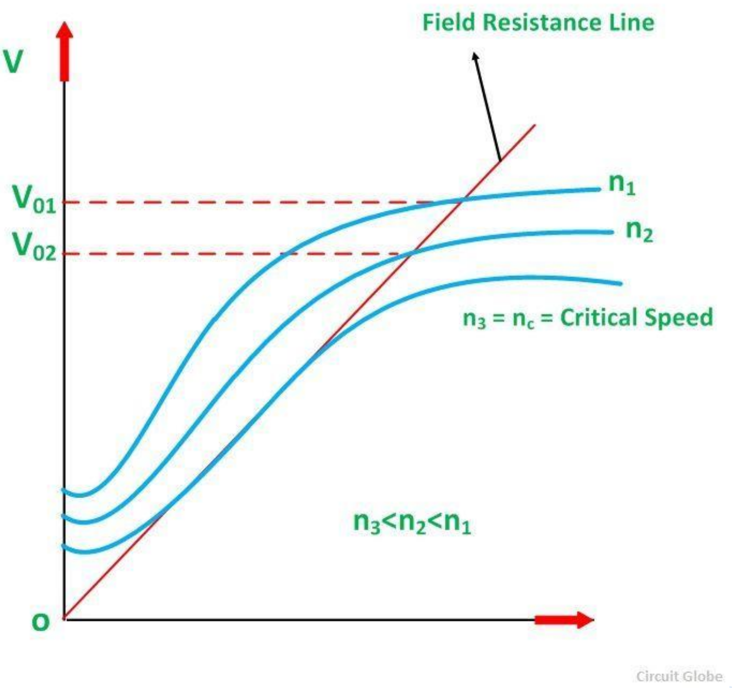


Effect of Field Resistance on No-Load Voltage

A decrease in the resistance of the field circuit reduces the slope of the field resistance line resulting in a higher voltage. An increase in the resistance of the field circuit increases the slope of the field resistance line, resulting in a lower voltage.

If the field circuit resistance is increased to Critical Resistance of the field (R_C), the field resistance line becomes tangent to the initial part of the magnetization curve.

If the value of field resistance is higher than the critical resistance of the field value, the generator fails to excite. The curve shown below gives the variation of no-load voltage with the fixed field resistance and the variable speed of the armature.



Variation of No-Load Voltage with Speed

The magnetization curve varies with the speed and its ordinates for any field current is proportional to the speed of the generator. If the field resistance is kept constant and the speed id reduced, all the points on the magnetization curve are lowered.

At a particular speed, called the **critical speed**, the field resistance line becomes tangential to the magnetization curve. Below the critical speed, the voltage will not build up.

The following conditions must be satisfied for voltage buildup in a self-excited DC generator.

- There must be a sufficient residual flux in the field poles.
- The field terminals should be connected in such a way that the field current increases flux in the direction of residual flux.
- The field circuit resistance should be less than the critical field circuit resistance.

If there is no residual flux in the field poles, disconnect the field from the armature circuit and apply a DC voltage to the field winding.

This process is called **Flashing the Field**.

2. INTERNAL OR TOTAL CHARACTERISTIC (E/I_A)

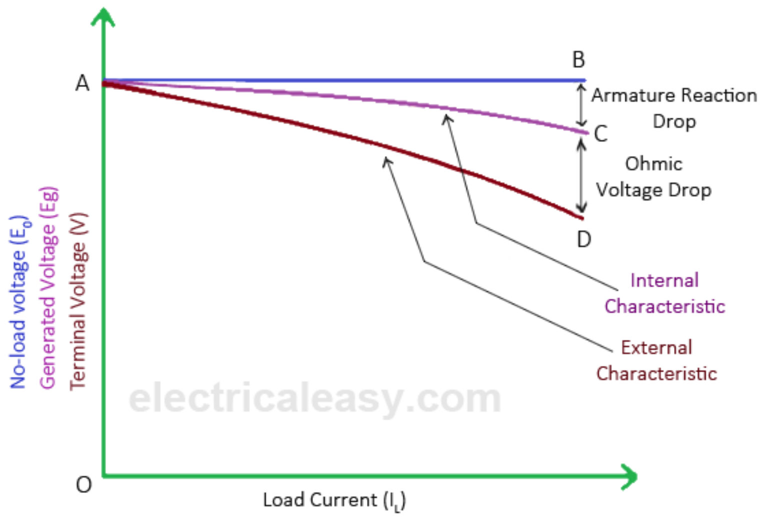
An internal characteristic curve shows the relation between the on-load generated emf (Eg) and the armature current (I_a). The on-load generated emf Eg is always less than E_0 due to the armature reaction. Eg can be determined by subtracting the drop due to demagnetizing effect of armature reaction from no-load voltage E_0. Therefore, internal characteristic curve lies below the O.C.C. curve.

3. EXTERNAL CHARACTERISTIC (V/I_L)

An external characteristic curve shows the relation between terminal voltage (V) and the load current (I_L). Terminal voltage V is less than the generated emf Eg due to voltage drop in the armature circuit. Therefore, external characteristic curve lies below the internal characteristic curve. External characteristics are very important to determine the suitability of a generator for a given purpose. Therefore, this type of characteristic is sometimes also called as **performance characteristic** or **load characteristic**.

Internal and external characteristic curves are shown below for each type of generator.

Characteristics Of Separately Excited DC Generator

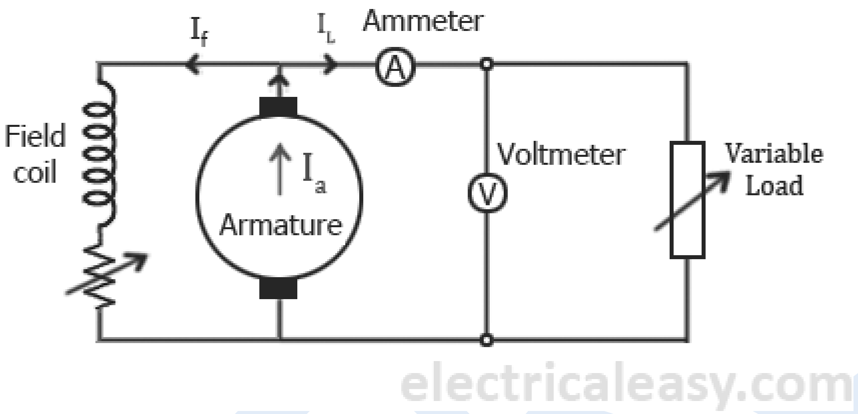


Characteristics of separately excited DC generator

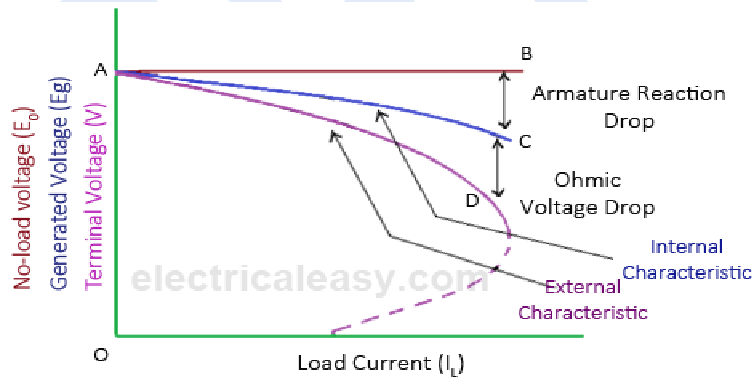
If there is no armature reaction and armature voltage drop, the voltage will remain constant for any load current. Thus, the straight line AB in above figure represents the no-load voltage vs. load current I_L. Due to the demagnetizing effect of armature reaction, the on-load generated emf is less than the no-load voltage. The curve AC represents the on-load generated emf Eg vs. load current I_L i.e. internal characteristic (as $I_a = I_L$ for a separately excited dc generator). Also, the terminal voltage is lesser due to ohmic drop occurring in the armature and brushes. The curve AD represents the terminal voltage vs. load current i.e. external characteristic.

Characteristics Of DC Shunt Generator

To determine the internal and external load characteristics of a DC shunt generator the machine is allowed to build up its voltage before applying any external load. To build up voltage of a shunt generator, the generator is driven at the rated speed by a prime mover. Initial voltage is induced due to residual magnetism in the field poles. The generator builds up its voltage as explained by the O.C.C. curve. When the generator has built up the voltage, it is gradually loaded with resistive load and readings are taken at suitable intervals. Connection arrangement is as shown in the figure below.



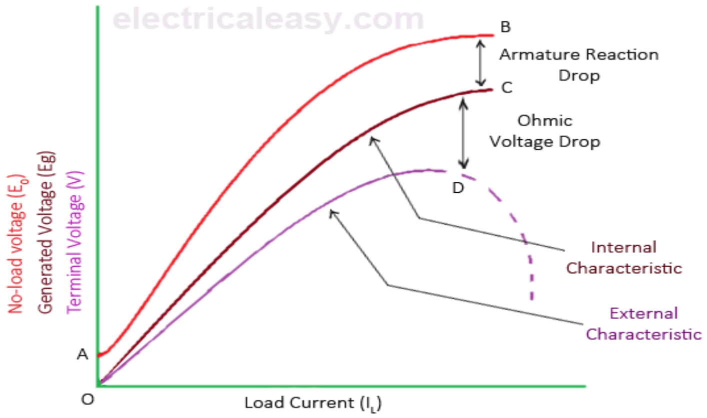
Unlike, separately excited DC generator, here, $I_L \neq I_a$. For a shunt generator, $I_a = I_L + I_f$. Hence, the internal characteristic can be easily transmitted to Eg vs. I_L by subtracting the correct value of I_f from I_a.



Characteristics of DC shunt generator

During a normal running condition, when load resistance is decreased, the load current increases. But, as we go on decreasing the load resistance, terminal voltage also falls. So, load resistance can be decreased up to a certain limit, after which the terminal voltage drastically decreases due to excessive armature reaction at very high armature current and increased I^2R losses. Hence, beyond this limit any further decrease in load resistance results in decreasing load current. Consequently, the external characteristic curve turns back as shown by dotted line in the above figure.

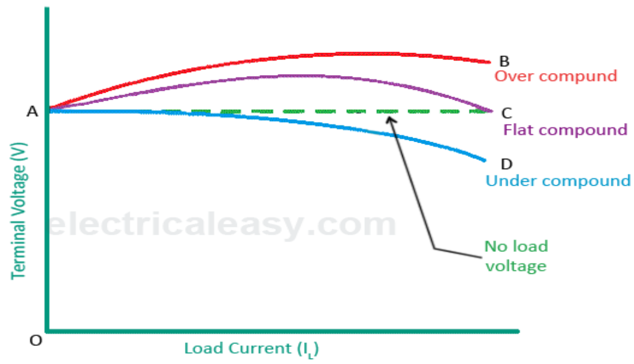
Characteristics Of DC Series Generator



Characteristics of DC series generator

The curve AB in above figure identical to open circuit characteristic (O.C.C.) curve. This is because in DC series generators field winding is connected in series with armature and load. Hence, here load current is similar to field current (i.e. $I_L=I_f$). The curve OC and OD represent internal and external characteristic respectively. In a DC series generator, terminal voltage increases with the load current. This is because, as the load current increases, field current also increases. However, beyond a certain limit, terminal voltage starts decreasing with increase in load. This is due to excessive demagnetizing effects of the armature reaction.

Characteristics Of DC Compound Generator



External characteristic of DC compound generator

The above figure shows the external characteristics of DC compound generators. If series winding amp-turns are adjusted so that, increase in load current causes increase in terminal voltage then the generator is called to be over compounded. The external characteristic for over compounded generator is shown by the curve AB in above figure.
If series winding amp-turns are adjusted so that, the terminal voltage remains constant even the load current is increased, then the generator is called to be flat compounded. The external characteristic for a flat compounded generator is shown by the curve AC.
If the series winding has lesser number of turns than that would be required to be flat compounded, then the generator is called to be under compounded. The external characteristics for an under compounded generator are shown by the curve AD.

DC MOTORS

A DC motor is an electrical machine that **converts electrical energy into mechanical energy**.

The working of DC motor is based on the principle that when a current carrying conductor is placed in a magnetic field, it experiences a mechanical force.

The direction of the mechanical force is given by **Fleming's Left-hand Rule** and its magnitude is given by **F = BIL** Newton.

The working of the AC motor (Induction motor and Synchronous Motor) is different from the DC motor.

There is no basic difference in the construction of a DC generator and a DC motor. In fact, the same DC machine can be used interchangeably as a generator or as a motor.

Like generators, there are different types of DC motors which are also classified into shunt-wound**,** series-wound **and compound-wound dc motors**.

DC motors are seldom used in ordinary applications because all electric supply companies furnish alternating current.

However, for special applications such as in **steel mills, mines, and** electric trains, it is advantageous to convert alternating current into direct current in order to use dc motors. The reason is that the **speed/torque** characteristics of DC motors are much more superior to that of AC motors.

Therefore, it is not surprising to note that for industrial drives, DC motors are as popular as three-phase induction motors.

DC Motor Principle

A machine that converts DC electrical power into mechanical power is known as a Direct Current motor.

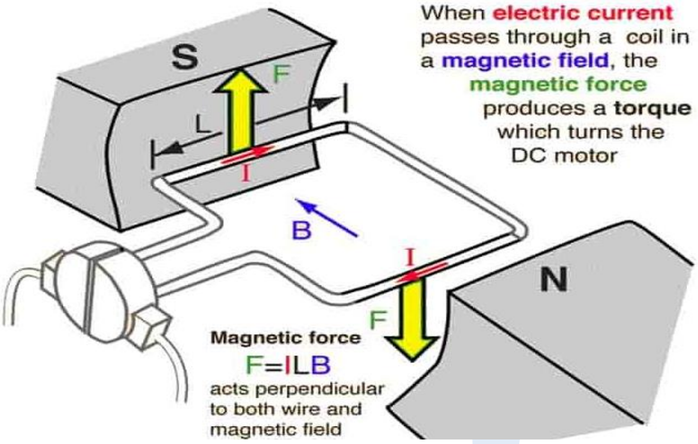
DC motor working is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.

The direction of this force is given by **Fleming's left-hand rule** and magnitude is given by;

F = BIL Newtons

According to Fleming's left-hand rule when an electric current passes through a coil in a magnetic field, the magnetic force produces a torque that turns the DC motor.

The direction of this force is perpendicular to both the wire and the magnetic field.

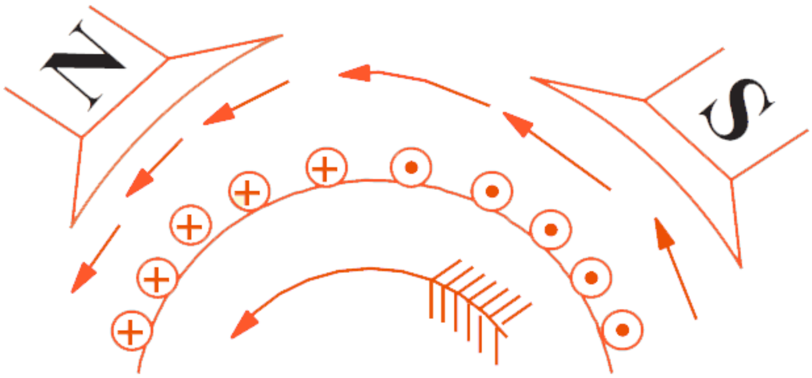


Basically, there is no constructional difference between a DC motor and a DC generator. The same DC machine can be run as a generator or motor.

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.

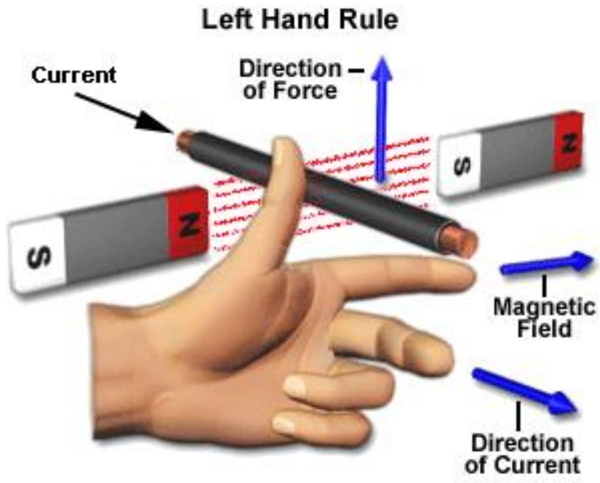


All conductors under North-pole carry currents in one direction while all the conductors under South-pole carry currents in the opposite direction.

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**.

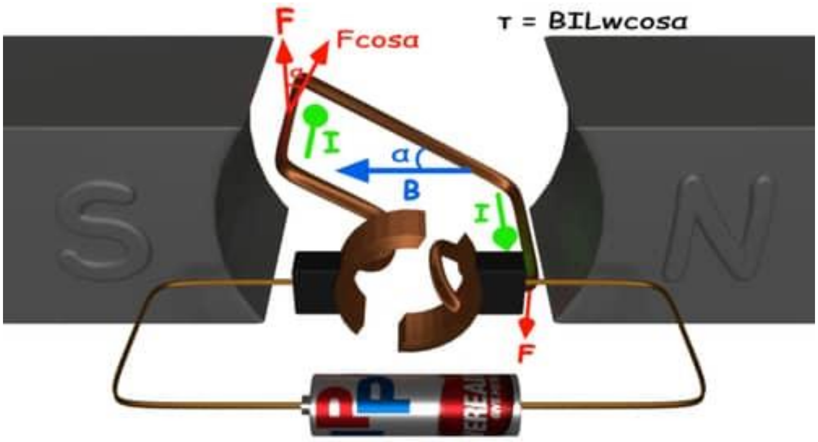
The torque produced is given by,

$$Torque = (force,\ tangential\ to\ the\ direction\ of\ armature\ rotation) \times (distance)$$

$$or,\ \tau = F \cos\alpha \times w$$

$$or,\ \tau = BILw \cos\alpha$$

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.



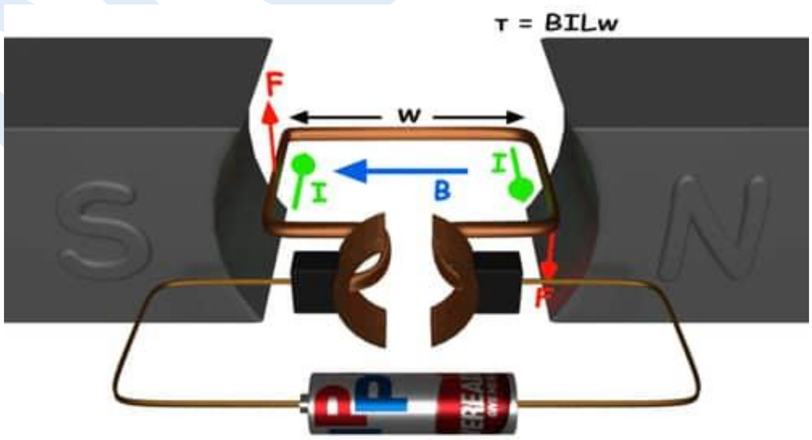
Step 1:

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.

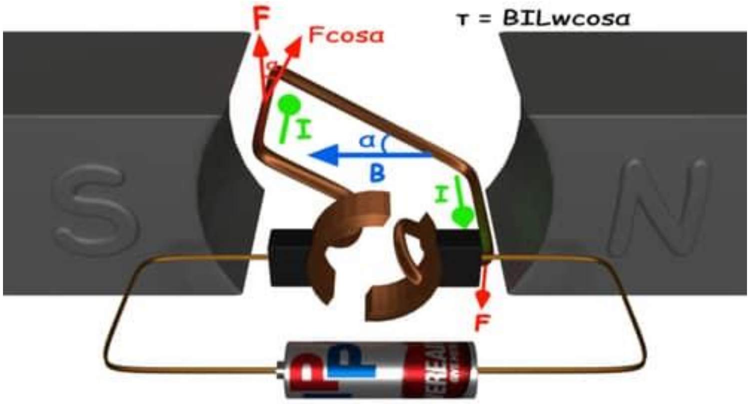


Step 2:

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.

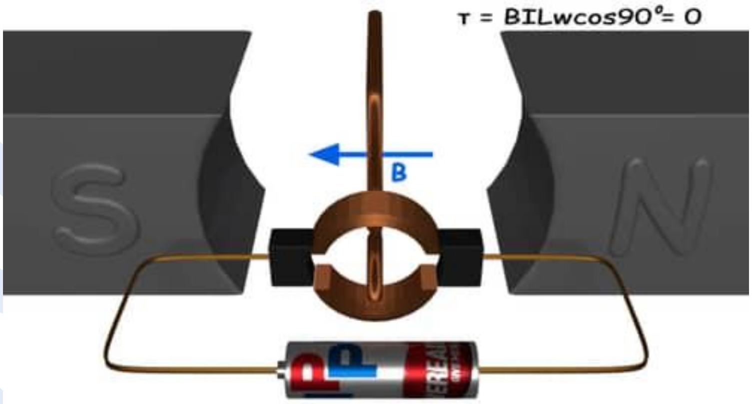
Consequently, the term cosα decreases and also the value of torque. The torque in this case is given by $\tau = BILw\cos\alpha$ which is less than BIL w when α is greater than

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. $\alpha = 90^o$, and as a result the term $\cos\alpha = 0$. 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

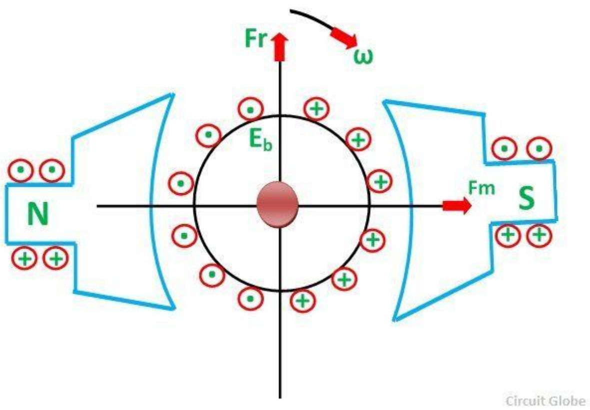
When the current-carrying conductor placed in a magnetic field, the torque induces on the conductor, the torque rotates the conductor which cuts the flux of the magnetic field. According to the Electromagnetic Induction Phenomenon "when the conductor cuts the magnetic field, EMF induces in the conductor"

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.

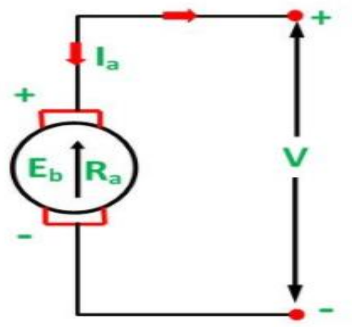


The magnitude of the back emf is given by the same expression shown below:

$$E_b = \frac{NP\varphi Z}{60\ A}$$

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 $E_b = V - I_aR_a$.

ADVANTAGES / SIGNIFICANCE OF BACK EMF IN DC MOTOR

1. The back emf opposes the supply voltage. The supply voltage induces the current in the coil which rotates the armature. The electrical work required by the motor for causing the current against the back emf is converted into mechanical energy. And that energy is induced in the armature of the motor. Thus, we can say that **energy conversion in the DC motor is possible only because of the back emf.**

The mechanical energy induced in the motor is the product of the back emf and the armature current, i.e., E_bI_a.

2. The back emf makes the DC motor self-regulating machine, i.e., **the back emf develops the armature current according to the need of the motor.** The armature current of the motor is calculated as

$$I = \frac{V - E_b}{R_a}$$

:

Let's understand how the back emf makes motor self-regulating.

- Consider the motor is running at no-load condition. At no load, the DC motor requires small torque for controlling the friction and windage loss. The motor withdraws less current. As the back emf depends on the current their value also decreases. The magnitude of the back EMF is nearly equal to the supply voltage.
- If the sudden load is applied to the motor, the motor becomes slow down. As the speed of the motor decreases, the magnitude of their back emf also falls down. The small back emf withdraw heavy current from the supply. The large armature current induces the large torque in the armature, which is the need of the motor. Thus, the motor moves continuously at a new speed.

- If the load on the motor is suddenly reduced, the driving torque on the motor is more than the load torque. The driving torque increases the speed of the motor which also increases their back emf. The high value of back emf decreases the armature current. The small magnitude of armature current develops less driving torque, which is equal to the load torque. And the motor will rotate uniformly at the new speed.

Relation between Mechanical power (Pm), supply voltage (Vt) and Back EMF (Eb)

The back emf in the dc motor is expressed as:

$$E_b = V_t - I_a R_a$$

Where E_b – Back Emf

I_a – Armature Current

V_t – Terminal Voltage

R_a – Resistance of Armature

The maximum power developed on the motor is expressed by

$$P_m = VI_a - 2I_a R_a$$

$$\frac{dP_m}{dI_a} = VI_a - 2I_a R_a$$

$$VI_a - 2I_a R_a = 0$$

$$V = 2I_a R_a$$

$$\frac{V}{2} = I_a R_a$$

On differentiating the above equation we get

From the back emf equation, we get

$$V = E_b + I_a R_a$$

On substituting the $I_a R_a$ in the above equation, we get

$$V = E_b + \frac{V}{2}$$

$$V - \frac{V}{2} = E_b$$

$$\frac{V}{2} = E_b$$

The above equation shows that the maximum power is developed in the motor when the back emf is equal to half of the supply voltage.

TYPES OF DC MOTOR

A Direct Current Motor, DC is named according to the connection of the field winding with the armature. Mainly there are two types of DC Motors. One is Separately Excited DC Motor and other is Self-excited DC Motor.

The self-excited motors are further classified as **Shunt wound** or shunt motor, **Series wound** or series motor and **Compound wound** or compound motor.

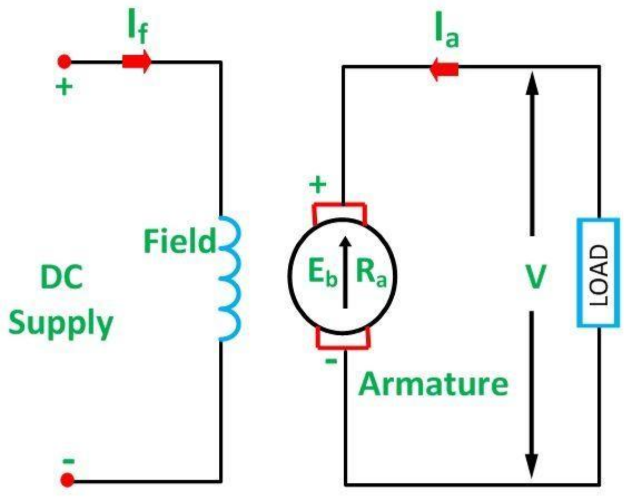
The dc motor converts electrical power into mechanical power. The construction of the dc motor and generator are the same. But the dc motor has a wide range of speed and good speed regulation in electric traction.

The working principle of the dc motor is based on the principle that the current-carrying conductor is placed in the magnetic field and a mechanical force is experienced by it.

The DC motor is generally used in the location that requires a protective enclosure, for example, drip-proof, the fireproof, etc. according to the requirements. The detailed description of the various types of motor is given below.

Separately Excited DC Motor

As the name signifies, the field coils or field windings are energised by a separate DC source as shown in the circuit diagram shown below:



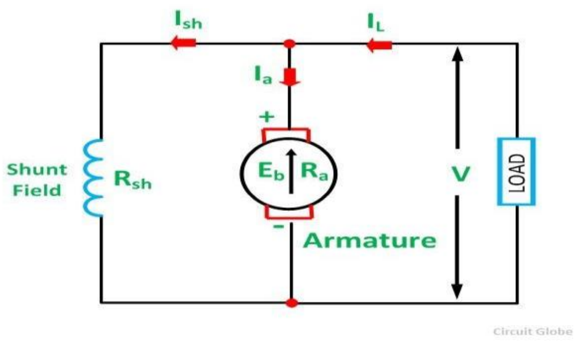
Separately Excited DC Motor

Self Excited DC Motor

As the name implies self-excited, hence, in this type of motor, the current in the windings is supplied by the machine or motor itself. Self-excited DC Motor is further divided into shunt wound, and series wound motor. They are explained below in detail.

Shunt Wound Motor

This is the most common types of DC Motor. Here the field winding is connected in parallel with the armature as shown in the figure below:



Shunt Wound DC Motor

The current, voltage and power equations for a shunt motor are written as follows.

By applying KCL at junction A in the above figure.

The sum of the incoming currents at A = Sum of the outgoing currents at A.

$$I = I_a + I_{sh} \dots\dots\dots (1)$$

Where,

I is the input line current

Ia is the armature current

Ish is the shunt field current

Equation (1) is the current equation.

The voltage equations are written by using Kirchhoff's voltage law (KVL) for the field winding circuit.

$$V = I_{sh}R_{sh} \dots\dots\dots (2)$$

For armature winding circuit the equation will be given as:

$$V = E + I_aR_a \dots\dots\dots (3)$$

The power equation is given as:

Power input = mechanical power developed + losses in the armature + loss in the field.

$$VI = P_m + I_a^2R_a + I_{sh}^2R_{sh} \dots\dots\dots (4)$$

$$VI = P_m + I_a^2R_a + VI_{sh}$$

$$P_m = VI - VI_{sh} - I_a^2R_a = V(I - I_{sh}) - I_a^2R_a$$

$$P_m = VI_a - I_a^2R_a = (V - I_aR_a)I_a$$

$$P_m = EI_a \dots\dots\dots (5)$$

Multiplying equation (3) by Ia we get the following equations.

$$VI_a = EI_a + I_a^2 R_a \dots\dots\dots (6)$$

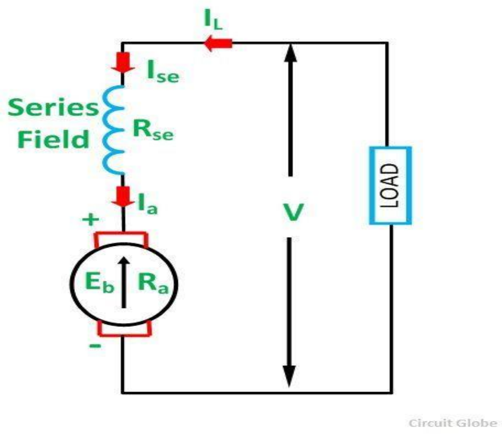
$$VI_a = P_m + I_a^2 R_a \dots\dots\dots (7)$$

Where,

VI_a is the electrical power supplied to the armature of the motor.

Series Wound Motor

In the series motor, the field winding is connected in series with the armature winding. The connection diagram is shown below:



Series Wound Motor

By applying the KCL in the above figure:

$$I = I_{se} = I_a$$

Where,

I_{se} is the series field current

The voltage equation can be obtained by applying KVL in the above figure.

$$V = E + I\,(R_a + R_{se}) \dots\dots\dots (8)$$

The power equation is obtained by multiplying equation (8) by I we get

$$VI = EI + I^2\,(R_a + R_{se}) \dots\dots\dots (9)$$

Power input = mechanical power developed + losses in the armature + losses in the field

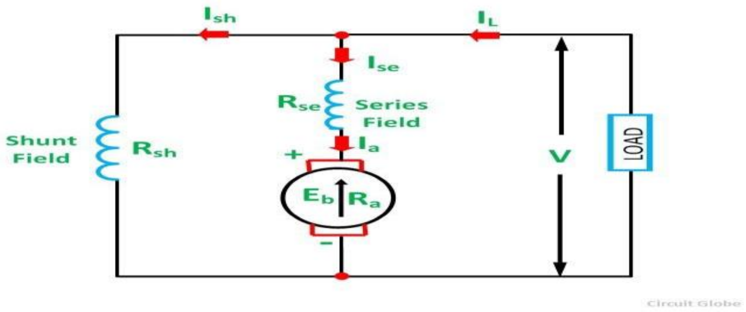
$$VI = P_m + I^2R_a + I^2R_a \dots\dots.(10)$$

Comparing the equation (9) and (10), we will get the equation shown below:

$$P_m = EI \dots\dots\dots(11)$$

Compound Wound Motor

A DC Motor having both shunt and series field windings is called a **Compound Motor**. The connection diagram of the compound motor is shown below:



Compound Motor

The compound motor is further subdivided as **Cumulative Compound** Motor and **Differential Compound** Motor. In a cumulative compound motor the flux produced by both the windings is in the same direction, i.e.

$$\varphi_r = \varphi_{sh} + \varphi_{se}$$

In differential compound motor, the flux produced by the series field windings is opposite to the flux produced by the shunt field winding, i.e.

$$\varphi_r = \varphi_{sh} - \varphi_{se}$$

The positive and negative sign indicates that the direction of the flux produced in the field windings.

TORQUE EQUATION OF A DC MOTOR

When a DC machine is loaded either as a motor or as a generator, the rotor conductors carry current. These conductors lie in the magnetic field of the air gap.

Thus, each conductor experiences a force. The conductors lie near the surface of the rotor at a common radius from its centre. Hence, a torque is produced around the circumference of the rotor, and the rotor starts rotating.

When the machine operates as a generator at a constant speed, this torque is equal and opposite to that provided by the prime mover.

When the machine is operating as a motor, the torque is transferred to the shaft of the rotor and drives the mechanical load. The expression is the same for the generator and motor.

When the current-carrying current is placed in the magnetic field, a force is exerted or it which exerts turning moment or torque F x r. This torque is produced due to the electromagnetic effect, hence is called **Electromagnetic torque.**

The torque which is produced in the armature is not fully used at the shaft for doing the useful work. Some part of it gets lost due to mechanical losses. The torque which is used for doing useful work in known as the **shaft torque**.

Since,

$$V = E_b + I_a R_a \quad \dots\dots(1)$$

Multiplying the equation (1) by I_a we get

$$VI_a = E_b I_a + I_a^2 R_a \quad \dots\dots(2)$$

Where,

VI_a is the electrical power input to the armature.

$I^2_a R_a$ is the copper loss in the armature.

We know that,

Total electrical power supplied to the armature = Mechanical power developed by the armature + losses due to armature resistance

Now, the mechanical power developed by the armature is Pm,

$$P_m = F_b I_a \dots\dots(3)$$

Also, the mechanical power that rotates the armature can be given regarding torque T and speed n.

$$P_m = \omega T = 2\pi nT \quad \ldots\ldots(4)$$

Where n is in revolution per seconds (rps) and T is in Newton-Meter.

Hence,

$$2\pi nT = E_b I_a \quad \text{or}$$

$$T = \frac{E_b I_a}{2\pi n}$$

But,

$$E_b = \frac{\varphi ZNP}{60\ A}$$

Where N is the speed in revolution per minute (rpm) and

$$n = \frac{N}{60}$$

Where n is the speed in (rps).

Therefore,

$$E_b = \frac{\varphi ZnP}{A}$$

So, the torque equation is given as:

$$T = \frac{\varphi ZP}{2\pi A} . I_a$$

For a particular DC Motor, the number of poles (P) and the number of conductors per parallel path (Z/A) are constant.

$$T = K\varphi I_a$$

Where

$$K = \frac{ZP}{2\pi A} \quad \text{or}$$

$$T \propto \varphi I_a \dots \dots (5)$$

Thus, from the above equation (5) it is clear that the torque produced in the armature is directly proportional to the flux per pole and the armature current.

Moreover, the direction of electromagnetic torque developed in the armature depends upon the current in armature conductors. If either of the two is reversed the direction of torque produced is reversed and hence the direction of rotation. But when both are reversed, and direction of torque does not change.

STARTING OF DC MOTORS

A **starter** is a device to start and accelerate a motor. A controller is a device to start the motor, control and reverse the speed of the DC motor and stop the motor. While starting the DC motor, it draws the heavy current which damages the motor.

The starter reduces the heavy current and protects the system from damage.

NEED OF STARTERS FOR DC MOTORS

The dc motor has no back emf. At the starting of the motor, the armature current is controlled by the resistance of the circuit. The resistance of the armature is low, and when the full voltage is applied at the standstill condition of the motor, the armature current becomes very high which damage the parts of the motor.

Because of the high armature current, the additional resistance is placed in the armature circuit at starting. The starting resistance of the machine is cut out of the circuit when the machine gains its speeds. The armature current of a motor is given by:

$$I_a = \frac{V - E}{R_a} \dots \dots \dots \quad (1)$$

Thus, I_a depends upon E and R_a, if V is kept constant. When the motor is first switched ON, the armature is stationary. Hence, the back EMF E_b is also zero. The initial starting armature current I_{as} is given by the equation shown below:

$$I_{as} = \frac{V - 0}{R_a} = \frac{V}{R_a} \ldots\ldots\ldots\ldots (2)$$

Since, the armature resistance of a motor is very small, generally less than one ohm. Therefore, the starting armature current I_{as} would be very large.

For example – if a motor with the armature resistance of 0.5 ohms is connected directly to a 230 V supply, then by putting the values in the equation (2) we will get,

$$I_{as} = \frac{V}{R_a} = \frac{230}{0.5} = 460 \quad \text{Ampere}$$

This large current would damage the brushes, commutator and windings.

As the motor speed increases, the back EMF increases and the difference (V – E) go on decreasing. This results in a gradual decrease of armature current until the motor attains its stable speed and the corresponding back EMF. Under this condition, the armature current reaches its desired value. Thus, it is found that the back EMF helps the armature resistance in limiting the current through the armature.

Since at the time of starting the DC Motor, the starting current is very large. At the time of starting of all DC Motors, except for very small motors, an extra resistance must be connected in series with the armature. This extra resistance is added so that a safe value of the motor is maintained and to limit the starting current until the motor has attained its stable speed.

The series resistance is divided into sections which are cut out one by one, as the speed of the motor rises and the back EMF builds up. The extra resistance is cut out when the speed of the motor builds up to its normal value.

Starters for Shunt and Compound Wound DC Motors:

A **3 point starter** is a device that helps in the starting and running of a DC shunt motor or compound wound DC motor (similar to a 4 point starter).

Now the question is why these types of DC motors require the assistance of the starter in the first place? Well, it’s due to the presence of back emf (E_b), which plays a critical role in governing the operation of the motor. The back emf develops as the motor armature starts to rotate in presence of the magnetic field, by generating action and counters the supply voltage. Hence the back emf at the starting of the motor is zero, but it develops gradually as the motor gathers speed.

The general motor emf equation is:

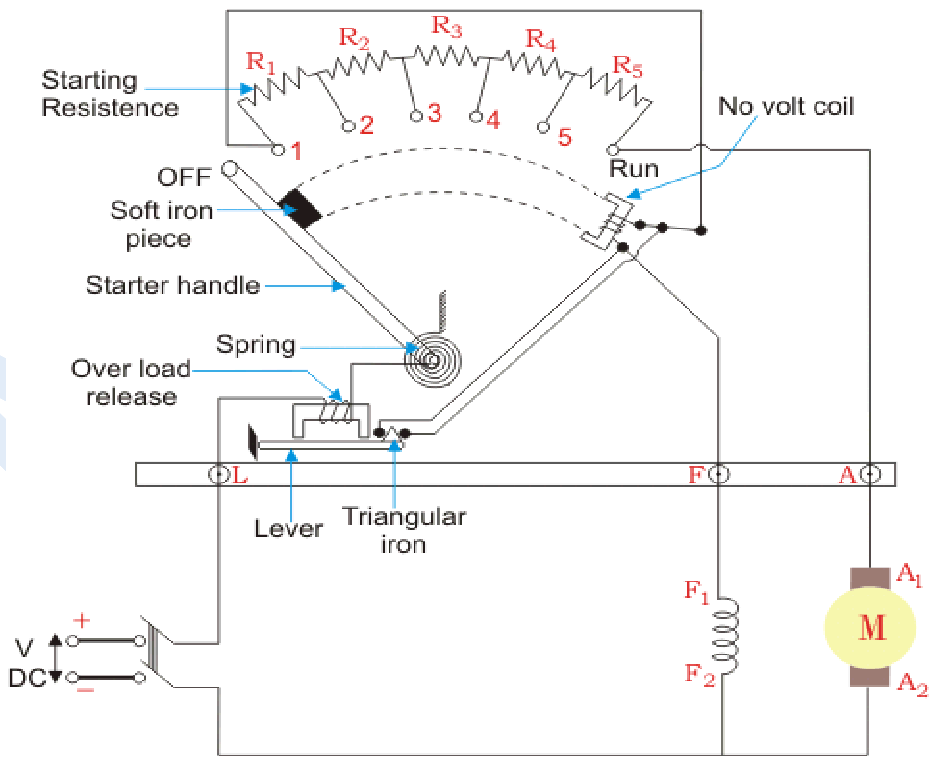
$$E = E_b + I_a . R_a$$

Where E=Supply Voltage; E_b=Back EMF; I_a=Armature Current; and R_a=Armature Resistance. Since at starting $E_b = 0$, then $E = I_a.R_a$. Hence we can rearrange for the armature current I_a:

$$\therefore\ I_a = \frac{E}{R_a}$$

We can see from the above equation that the current will be dangerously high at starting (as the armature resistance R_a is small). This is why it's important that we make use of a device like the **3 point starter** to limit the starting current to acceptably low value.

To understand how the starting current is restricted to the desired value, we need to look at the construction and **working of three-point starter**. The electrical symbols in the diagram below show all the essential parts of a three-point starter.



3 Point Starter Diagram

Construction of 3 Point Starter

Construction wise a starter is a variable resistance, integrated into the number of sections as shown in the figure beside. The contact points of these sections are called studs and are shown separately as **OFF, 1, 2, 3, 4, 5, RUN**. Other than that there are three main points, referred to as

1. 'L' Line terminal (Connected to positive of supply)
2. 'A' Armature terminal (Connected to the armature winding)
3. 'F' Field terminal (Connected to the field winding)

And from there it gets the name 3 point starter. Now studying the **construction of 3 point starter** in further details reveals that the point 'L' is connected to an electromagnet called overload release (OLR) as shown in the figure. The other end of OLR is connected to the lower end of conducting lever of starter handle where spring is also attached with it, and the starter handle also contains a soft iron piece housed on it. This handle is free to move to the other side RUN against the force of the spring. This spring brings back the handle to its original OFF position under the influence of its own force. Another parallel path is derived from the stud '1', given to another electromagnet called No Volt Coil (NVC) which is further connected to terminal 'F.' The starting resistance at starting is entirely in series with the armature. The OLR and NVC act as the two protecting devices of the starter.

Working of Three Point Starter

Having studied its construction, let us now go into the **working of the 3 point starter**. To start with the handle is in the OFF position when the supply to the DC motor is switched on. Then handle is slowly moved against the spring force to make contact with stud No. 1. At this point, field winding of the shunt or the compound motor gets supply through the parallel path provided to starting the resistance, through No Voltage Coil. While entire starting resistance comes in series with the armature. The high starting armature current thus gets limited as the current equation at this stage becomes:

$$I_a = \frac{E}{(R_a + R_{st})}$$

As the handle is moved further, it goes on making contact with studs 2, 3, 4, etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed. Finally, when the starter handle is in 'RUN' position, the entire starting resistance is eliminated, and the motor runs with normal speed.

This is because back emf is developed consequently with speed to counter the supply voltage and reduce the armature current.

So the external electrical resistance is not required anymore and is removed for optimum operation. The handle is moved manually from OFF to the RUN position with the development of speed. Now the obvious question is once the handle is taken to the RUN position how it is supposed to stay there, as long as the motor is running.

To find the answer to this question let us look into the working of No Voltage Coil.

Working of No Voltage Coil of 3 Point Starter

The supply to the field winding is derived through no voltage coil. So when field current flows, the NVC is magnetized. Now when the handle is in the 'RUN' position, a soft iron piece is connected to the handle and gets attracted by the magnetic force produced by NVC, because of flow of current through it. The NVC is designed in such a way that it holds the handle in 'RUN' position against the force of the spring as long as supply is given to the motor. Thus NVC holds the handle in the 'RUN' position and hence also called **hold on coil**.

Now when there is any kind of supply failure, the current flow through NVC is affected and it immediately loses its magnetic property and is unable to keep the soft iron piece on the handle, attracted. At this point under the action of the spring force, the handle comes back to OFF position, opening the circuit and thus switching off the motor. So due to the combination of NVC and the spring, the starter handle always comes back to OFF position whenever there is any supply problem. Thus it also acts as a protective device safeguarding the motor from any kind of abnormality.

Drawbacks of a Three Point Starter

The **3 point starter** suffers from a serious drawback for motors with a large variation of speed by adjustment of the field rheostat. To increase the speed of the motor field resistance can be increased. Therefore current through the shunt field is reduced.

Field current becomes very low which results in holding electromagnet too weak to overcome the force exerted by the spring. The holding magnet may release the arm of the starter during the normal operation of the motor and thus disconnect the motor from the line. This is not desirable. A 4 point starter is thus used instead, which does not have this drawback.

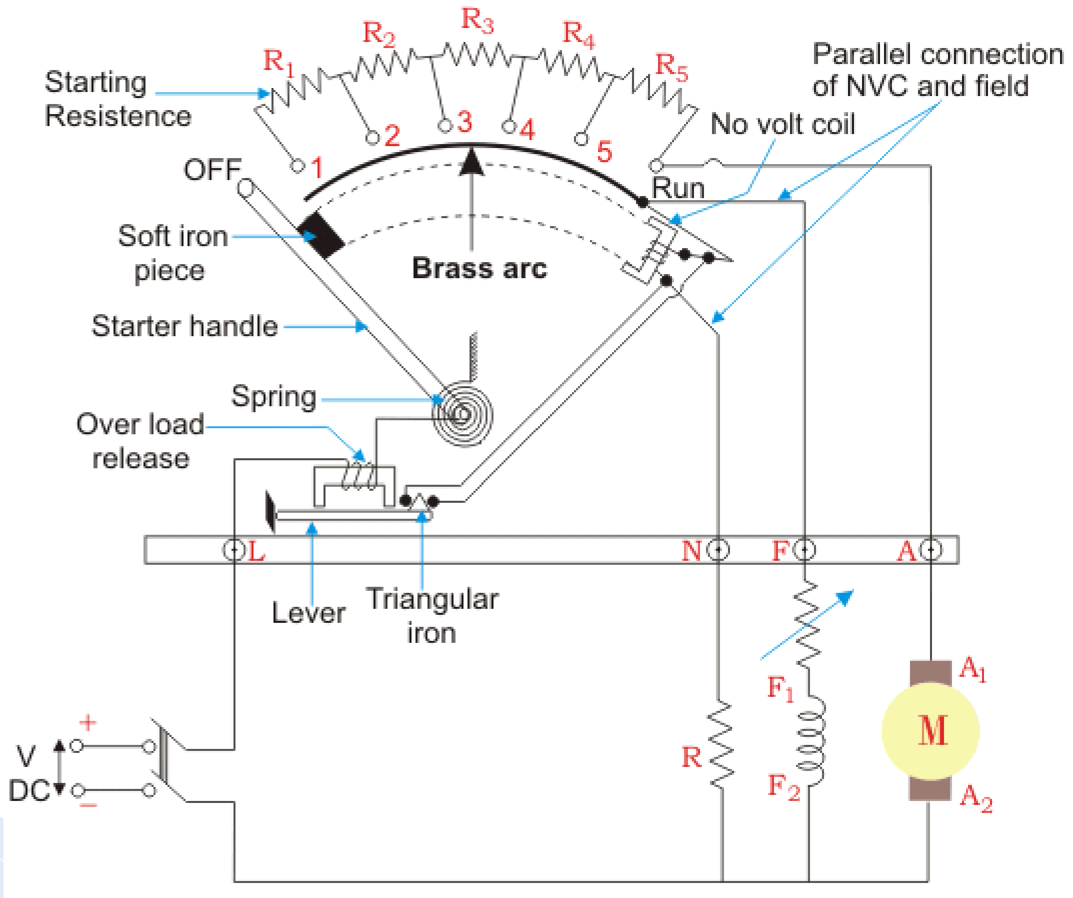
FOUR POINT STARTER

Construction and Operation of Four Point Starter

A 4 point starter as the name suggests has 4 main operational points, namely

1. 'L' Line terminal (Connected to positive of supply.)
2. 'A' Armature terminal (Connected to the armature winding.)
3. 'F' Field terminal. (Connected to the field winding.)
4. Like in the case of the 3 point starter, and in addition to it there is, A 4th point N (Connected to the No Voltage Coil NVC)

The remarkable difference in case of a 4 point starter is that the No Voltage Coil is connected independently across the supply through the fourth terminal called ‘N’ in addition to the ‘L’, ‘F’ and ‘A’. As a direct consequence of that, any change in the field supply current does not bring about any difference in the performance of the NVC. Thus it must be ensured that no voltage coil always produce a force which is strong enough to hold the handle in its ‘RUN’ position, against the force of the spring, under all the operational conditions. Such a current is adjusted through No Voltage Coil with the help of fixed resistance R connected in series with the NVC using fourth point ‘N’ as shown in the figure above.



4 Point Starter Diagram

Apart from this above mentioned fact, the 4 point and 3 point starters are similar in all other ways like possessing is a variable resistance, integrated into number of sections as shown in the figure above. The contact points of these sections are called studs and are shown separately as OFF, 1, 2, 3, 4, 5, RUN, over which the handle is free to be maneuvered manually to regulate the starting current with gathering speed.

Now to understand its way of operating let’s have a closer look at the diagram given above. Considering that supply is given and the handle is taken stud No.1, then the circuit is complete and the line current that starts flowing through the starter. In this situation we can see that the current will be divided into 3 parts, flowing through 3 different points.

1. 1 part flows through the starting resistance (R_1+ R_2 + R_3…..) and then to the armature.

2. A 2nd part flowing through the field winding F.
3. And a 3rd part flowing through the no voltage coil in series with the protective resistance R.

So the point to be noted here is that with this particular arrangement any change in the shunt field circuit does not bring about any change in the no voltage coil as the two circuits are independent of each other.

This essentially means that the electromagnet pull subjected upon the soft iron bar of the handle by the no voltage coil at all points of time should be high enough to keep the handle at its RUN position, or rather prevent the spring force from restoring the handle at its original OFF position, irrespective of how the field rheostat is adjusted.

This marks the operational difference between a **4 point starter** and a 3 point starter. As otherwise both are almost similar and are used for limiting the starting current to a shunt wound DC motor or compound wound DC motor, and thus act as a protective device.

DC SERIES MOTOR STARTER:

The series motor starter serves the same purpose as the three- and four-point starters employed with shunt and compound wound motors. However, series motor starter has different internal and external connections.

TWO POINT STARTER

Three point and four point starters are used for d.c. shunt motors.

In case of series motors, field and armature are inserted and hence starting resistance is inserted in series with the field and armature.

Such a starter used to limit the star4ting current in case of dc series motor is called two point starters.

The basic construction of two point starter is similar to that of three point starter the fact that is has only two terminal namely line (L) and field F.

The terminal is one end of the series combination of field and the armature winding. The action of the starter is similar to that of three point starter. The handle of the starter is in OFF position. When it is moved to on, motor gets the supply and the entire starting resistance is in series with the armature and field. It limits the starting current.

The current through no volt coil energizes it and when handle reaches to RUN position, the no volt coil holds the handle by attracting the soft iron piece on the handle. Hence the no volt coil is also called hold on coil.

The main problem in case of dc series motor is it over speeding action when the load is less. This can be prevented using two point starters. The no volt coil is designed in such a way that it holds the handle in RUN positions only when it carries sufficient current, for which motor can run safely.

If there is loss of load then current drawn by the motor decreases, due to which no volt coil losses its required magnetism and releases the handle. Under spring force, handle comes back to OFF position, protecting the motor from over speeding. Similarly if there is any supply problem such that voltage decreases suddenly conditions.

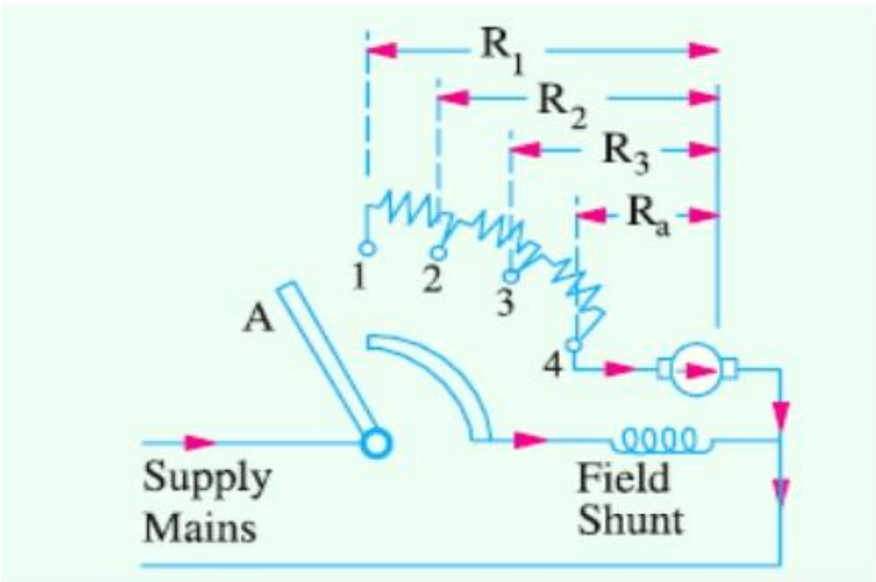


Fig 3.3 Two Point Starter

The overload condition can be prevented using overload magnet increases. This energizes the magnet up to such an extent that it attracts the lever below it. When lever is lifted upwards, the triangular piece attached to it touches the two pints, which are the two ends of no volt coil.

Thus no volt coil gets shorted, loosing its magnetism and releasing the handle back to OFF position. This protects the motor from overloading conditions.

POWER FLOW DIAGRAM IN DC MACHINES

There are 2 main categories of dc machines first one is DC motor and the second one is DC generator. The motor converts electrical power into the mechanical power and dc generator transforms mechanical power into electrical power. During these power conversions either mechanical to electrical or electrical to mechanical, some power losses occur that decrease the quantity of power conversion.

Due to these power losses heating produces that affect the operation of dc machines. Due to these power losses the efficiency of machines also decreases. In today's post, we will have a detailed look at these power losses and their effects on machines. Also, discuss how we can reduce these power losses. So let's get started with the *Power Flow and Losses in Dc Machines.*

Power Flow and Losses in DC Machines

- The efficiency of any dc machine either dc motor or generator is given as.

  $=(P_{out}/P_{in}) \times 100\%$

- If we define the losses that we will find that it is the difference between input and output power of dc machines.
- In the mathematical expression, it can be defined as.

  $=(P_{out}-P_{loss})/(P_{in}) \times 100\%$

- There are 5 main types of losses that occur in dc machines either its motor or generator.
- Copper Losses or I^2R Losses
- Brush Losses
- Core Losses
- Mechanical Losses
- Stray Losses

Now we discuss all these losses one by one with the detailed.

Copper Losses

- As you can understand from the name of these losses that are copper losses mean that losses occur at the windings of machines.
- There are 2 types of windings first one is field winding that exists at the stator and the second one is armature windings that exit at the rotor, at these two windings coppers losses occurs.
- The value of these losses for armature and copper windings can be given as.

Armature winding losses = $P_A = I_A^2 R_A$

Field winding losses = $P_F = I_F^2 R_F$

- In these two above given equations.
- P_A stands for armature losses.
- P_F field windings losses.
- I_A is current passing through the armature winding.
- I_F is current passing through the stator windings.
- R_A is armature resistance.
- R_F is field windings resistance.

Brush Losses

- These losses occur at the carbon brushes that are connected with the output terminals and commutators of machines.
- The mathematical expression for these brushes is given as.

$P_{BD}=V_{BD}I_A$

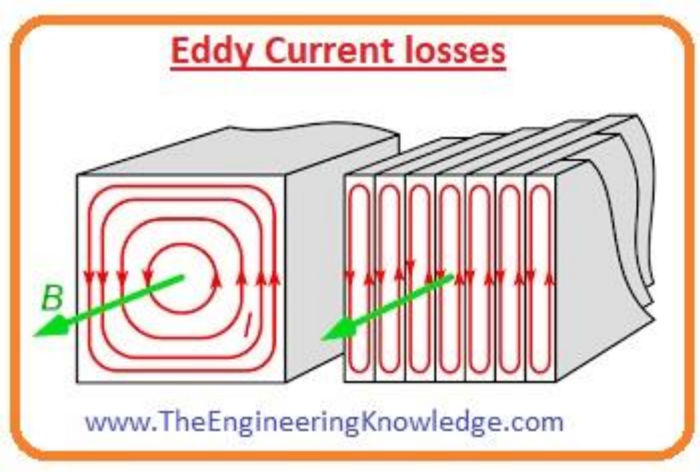
- In this equation.
- P_{BD} is the loss at the carbon brushes.
- V_{BD} voltage losses at the brushes.
- I_A is the armature current.
- The purpose that the brush losses are found in this way is that the voltage drop at the brushes remains same at the different values of currents.

Core Losses in DC Machines

- There are two types of copper losses in dc machines first one is eddy current losses and the second one is hysteresis losses.

Eddy Current losses

- If we discuss Faraday law that says that the rate of change of flux in any conductor produces a voltage in that conductor.



EMF =dø/dt

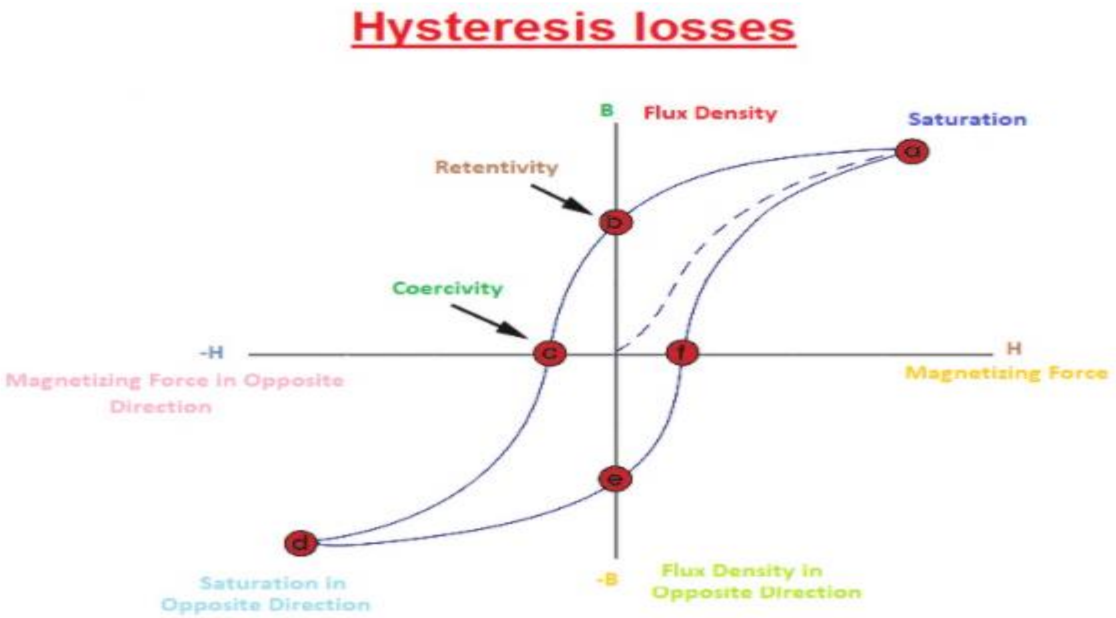
- If we apply this law on dc machine that we come to know that when the rotor of the machine rotates in the field of the rotor than voltage induces in the rotor that current starts to flow through the armature winding this current known as eddy current.
- The mathematical expression for these current is given as.

$$P_e = K_e x B_{max}^2 \text{ x } f^2 \text{ x } t^2 \text{ x } V$$

- We can describe here the component of this equation as.
- P_e stands the power losses due to eddy currents.
- K_e is constant for these currents.
- B is flux density.
- f is the frequency.
- t is the thickness of the materials used.
- V is the volume of the core of machines

Hysteresis loss

- The cause of these losses is the energy required to magnetize and demagnetize the core of the machine.



- With the increment in current for magnetization of core, the value of flux also increases.
- But when we decrease the current that used for magnetization the value of corresponding flux don not decreases with the current.
- When the value of the current becomes zero then there is some value of flux exits in the core.
- To minimize the flux in the core and external force is applied that causes hysteresis losses. The opposite polarity of field is provided to the core that minimizes the ramming flux in the machine.
- The negative magnetization depends on the material used for the construction of core.
- The mathematical expression for these losses is given as.

$$P_b = \eta \text{ x } B_{max}^{n} \text{ x } f \text{ x } V$$

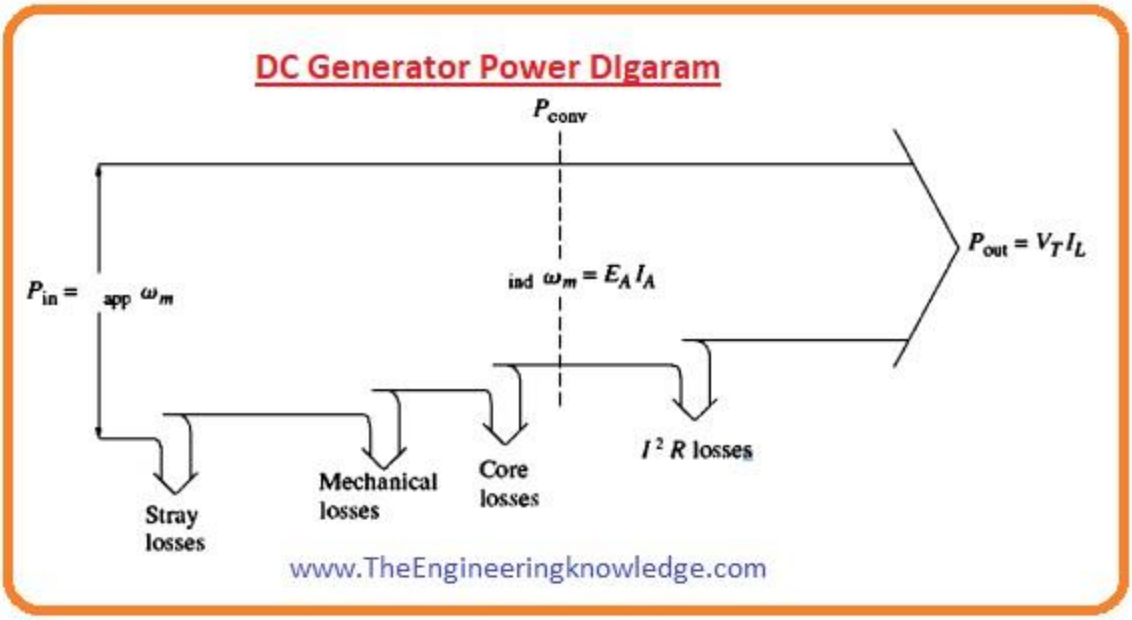
- In this equation.
- P_b denotes the hysteresis losses
- H is Steinmetz hysteresis coefficient. Its value is from 1.5 to 2.5l
- B_{max}^{n} is flux density.
- f is frequency.
- V is volume of material used for core construction.
- In the given figure, you can see the curve for these losses.

Mechanical Losses

- These losses occur in dc machines due to the mechanical effects that occur in dc machines. These are 2 main facts that cause to mechanical losses first one is friction and second is windage
- Friction losses occur due to the bearings that exit the shaft of machines. The windage losses occur due to the air among the rotatory portion and their casing.
- These losses changes with the cube of speed of revolution of the machine.

DC Machines Power-Flow Diagram

- One of the simple methods to find the values of different losses in dc machines is to draw their power flow diagram.
- In the given figure, you can see the power diagram of dc generator.



- In this figure the mechanical power is input and after eliminating stray losses, mechanical losses (friction and windage losses), core losses than we have an electrical output that is given here.

  Input as mechanical power.

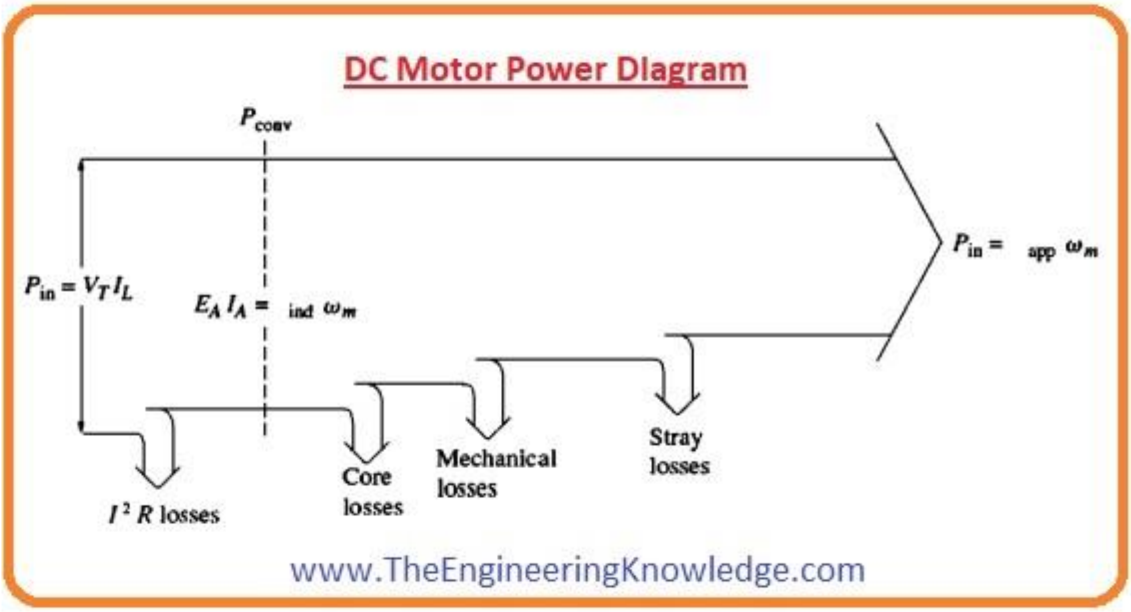
$$P_{conv} = t_{ind} w_m$$

  Output power is given here.

$$P_{conv} = E_A I_A$$

- But, this is not the power that gets at the output terminals. Before reaching at the output terminal copper losses and brush losses also subtract from it.

- In the given figure the dc motor power flow diagram is given it is the reverse of dc generator power flow figure.



MODULE V

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.

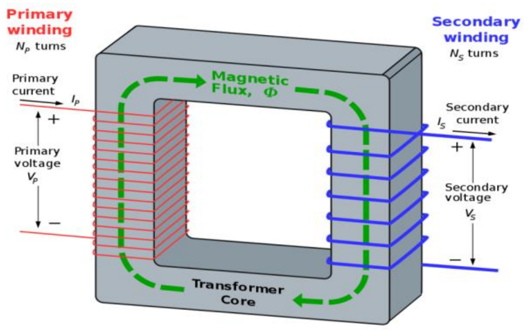
In a broad, transformers are categorized into two types, namely, electronic transformers and power transformers. Electronic transformers operating voltages are very low and are rated at low power levels. These are used in consumer electronic equipments like televisions, personal computers, CD/DVD players, 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.



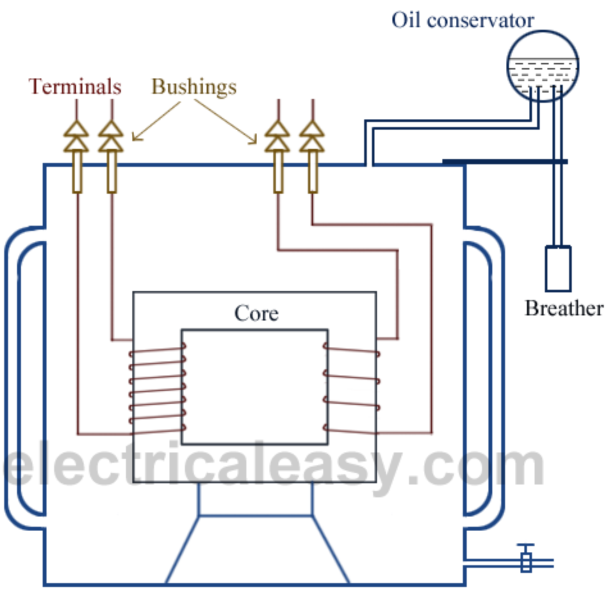
Electric transformer

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.

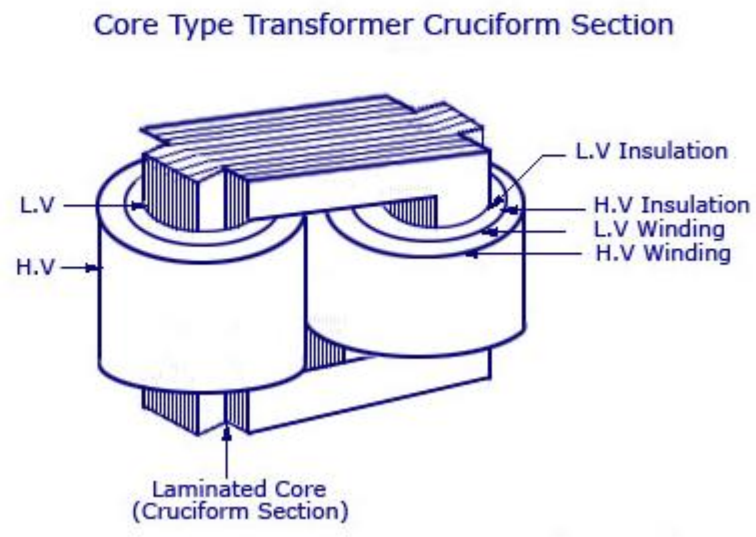
In all types of transformers, core is made up of silicon steel or sheet steel laminations which are assembled to provide a continuous magnetic path for the flux. With this laminated core eddy current losses are minimized.

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.

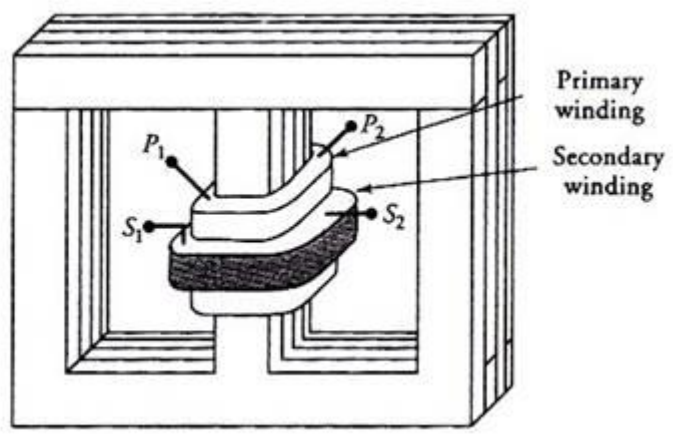
And for a large sized core type transformer, cruciform core with round or circular cylindrical coils are used. In most of the core type transformers, cylindrical coils are used due to their mechanical strength. These cylindrical coils are wound in helical layers and are insulated from each other by insulating 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

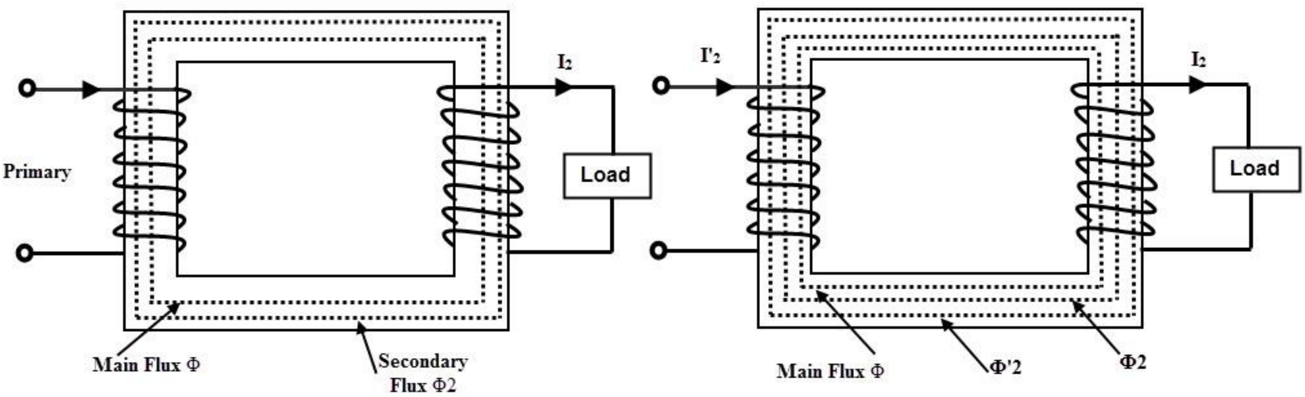
The operation of the transformer is based on the principle of mutual induction between two coils or winding which are linked by a common magnetic flux. When the primary winding is energized with AC source supply, a magnetic flux is established in the primary winding.

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

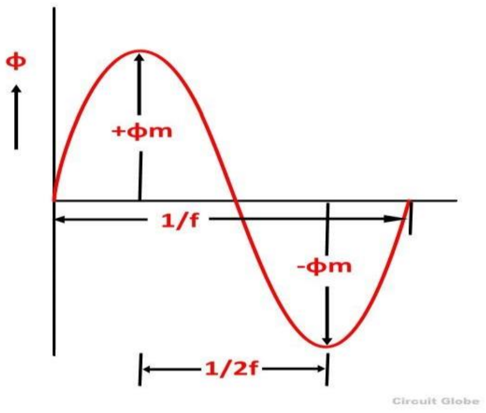
When a sinusoidal voltage is applied to the primary winding of a transformer, alternating flux ϕ_m sets up in the iron core of the transformer. This sinusoidal flux links with both primary and secondary winding. The function of flux is a sine function.

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

$$E_1 = -\frac{d\psi}{dt} \dots\dots\dots (1)$$

Where $\Psi = N_1\phi$

$$\text{Therefore, } E_1 = -N_1 \frac{d\varphi}{dt} \dots\dots\dots (2)$$

Since ϕ is due to AC supply $\phi = \phi_m$ Sinwt

$$E_1 = -N_1 \frac{d}{dt} (\varphi_m \,\mathrm{Sinwt})$$

$$E_1 = -N_1\, w\varphi_m \,\mathrm{Coswt}$$

$$E_1 = N_1 w\varphi_m \,\mathrm{Sin}(wt - \pi/2) \dots\dots\dots (3)$$

So the induced emf lags flux by 90 degrees.

Maximum valve of emf

$$E_1 max = N_1 w\varphi_m \dots\dots\dots (4)$$

But $w = 2\pi f$

$$E_1 max = 2\pi f N_1 \varphi_m \dots\dots\dots (5)$$

Root mean square RMS value is

$$E_1 = \frac{E_{1max}}{\sqrt{2}} \dots\dots\dots (6)$$

Putting the value of E_1max in equation (6) we get

$$E_1 = \sqrt{2}\pi f N_1 \varphi_m \dots\dots (7)$$

Putting the value of π = 3.14 in the equation (7) we will get the value of E_1 as

$$E_1 = 4.44fN_1\varphi_m \dots\dots\dots(8)$$

Similarly

$$E_2 = \sqrt{2}\pi fN_2\varphi_m$$

Or

$$E_2 = 4.44fN_2\varphi_m \dots\dots\dots(9)$$

Now, equating the equation (8) and (9) we get

$$\frac{E_2}{E_1} = \frac{4.44fN_2\varphi_m}{4.44fN_1\varphi_m}$$

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.

$$E_1 = 4.44N_1fB_mA_i \text{ Volts} \quad \text{and} \quad E_2 = 4.44N_2fB_mA_i \text{ Volts}$$

$$\frac{\text{R.M.S value}}{\text{Average value}} = \text{Form factor} = 1.11$$

For a sinusoidal wave

Here 1.11 is the form factor.

It's seen from *(i)* and *(ii)* that: **EMF Equation of the Transformer =**

$$E_1 / N_1 = E_2 / N_2 = 4.44 \times f\, \Phi_m. \quad \ldots\ldots (i)$$

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

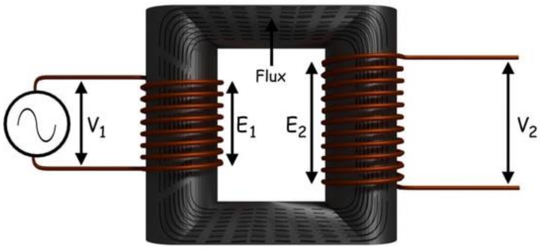
An **ideal transformer** is an imaginary transformer which has

- *no copper losses (no winding resistance)*

- *no iron loss in core*

- *no leakage flux*

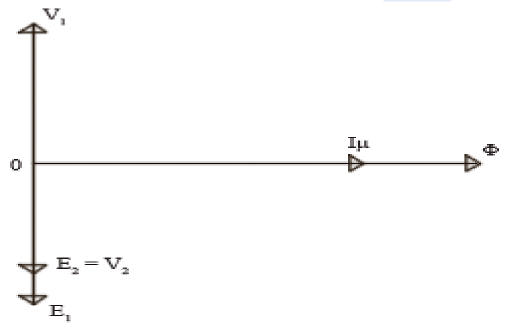
In other words, an ideal transformer gives output power exactly equal to the input power. The **efficiency of an idea transformer** is 100%. Actually, it is impossible to have such a transformer in practice, but **ideal transformer model** makes problems easier.



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.

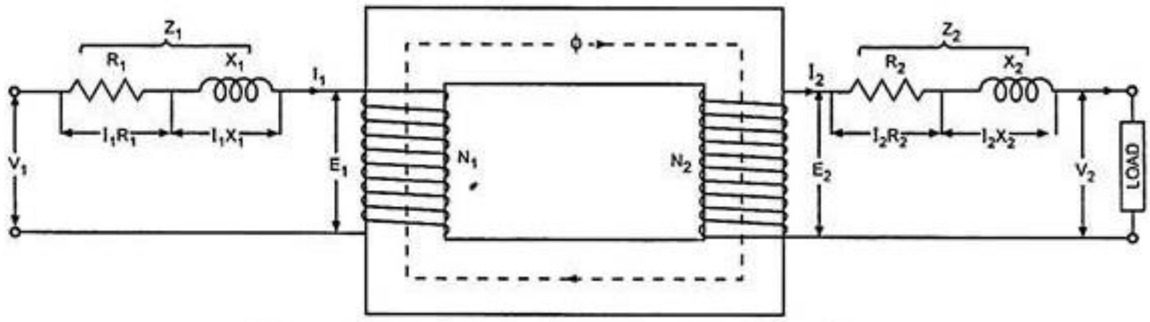


Now, if an alternating voltage V_1 is applied to the primary winding of an ideal transformer, counter emf E_1 will be induced in the primary winding. As windings are purely inductive, this induced emf E_1 will be exactly equal to the apply voltage but in 180 degree phase opposition. Current drawn from 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, $E_1I_1 = E_2I_2$.

PHASOR DIAGRAMS OF TRANSFORMERS

Consider a transformer shown in Fig. 10.13 having primary and secondary windings of resistances R_1 and R_2 and reactance X_1 and X_2 respectively. The impedance of primary winding is given by $Z_1 = R_1 + j X_1$ and impedance of secondary winding is given by $Z_2 = R_2 + jX_2$.



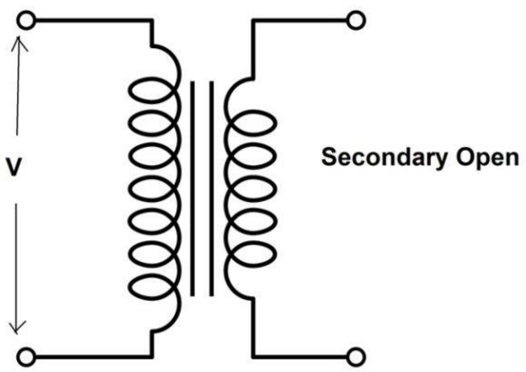
An Equivalent Diagram of Actual Transformer

Important Points For Phasor Of Transformer

- Transformer when excited at no load, only takes excitation current which leads the working Flux by Hysteretic angle α.
- Excitation current is made up of two components, one in phase with the applied Voltage V is called Core Loss component (Ic) and another in phase with the working Flux Ø called Magnetizing Current (Im).
- Electromotive Force (EMF) created by working Flux Ø lags behind it by 90 degree.
- When Transformer is connected with a Load, it takes extra current I' from the Source so that N 1I' = N 2 I 2 where I' is called load componete of Primary Current I
- So under load condition, I 1 = Primary Current, is phasor Sum of I' and Excitation Current Ie.

Phasor Diagram for No Load Condition:

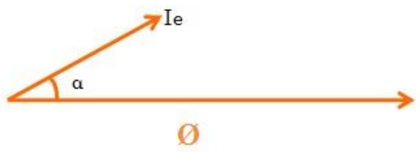
Transformer at no load means that its secondary winding is open and primary is energized from voltage source. Figure below shows this condition.



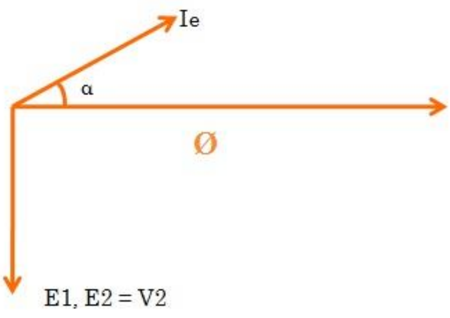
Following steps should be followed for phasor diagram of transformer at no load condition:

- Working Flux Ø taken as Reference as shown below.

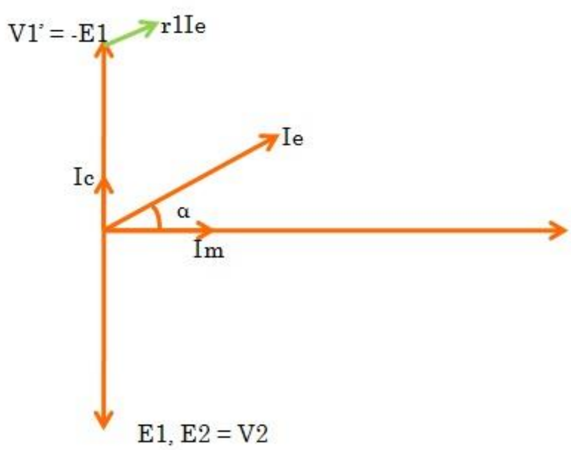
- Excitation Current I_e leading Ø by α.



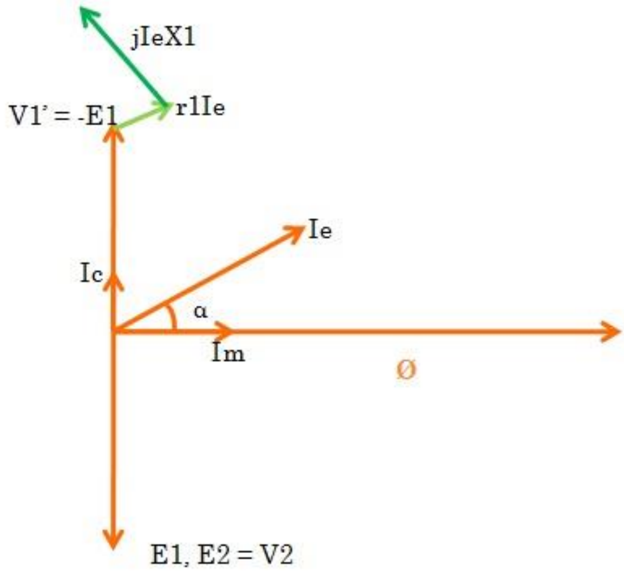
- Induced EMF E_1 and E_2 lagging Flux by 90 degree.



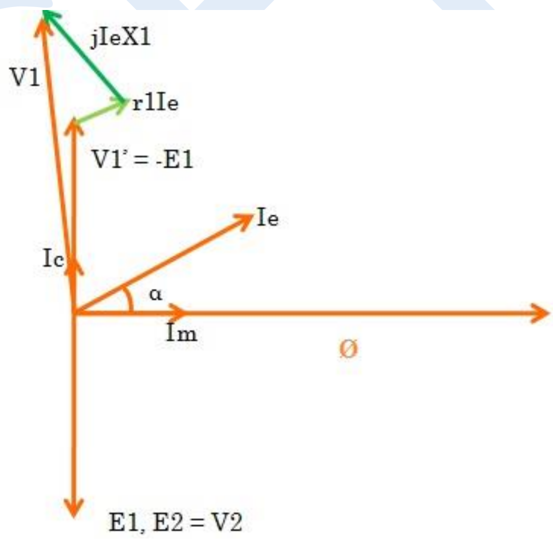
- Voltage drop r_1I_e in Primary. This will be in phase with the I_e and hence shown parallel to it in the figure below.



- Voltage drop I_eX_1 in Primary due to reactance. This will be perpendicular to I_e as shown below. (Why perpendicular to I_e? Please write in comment box.)



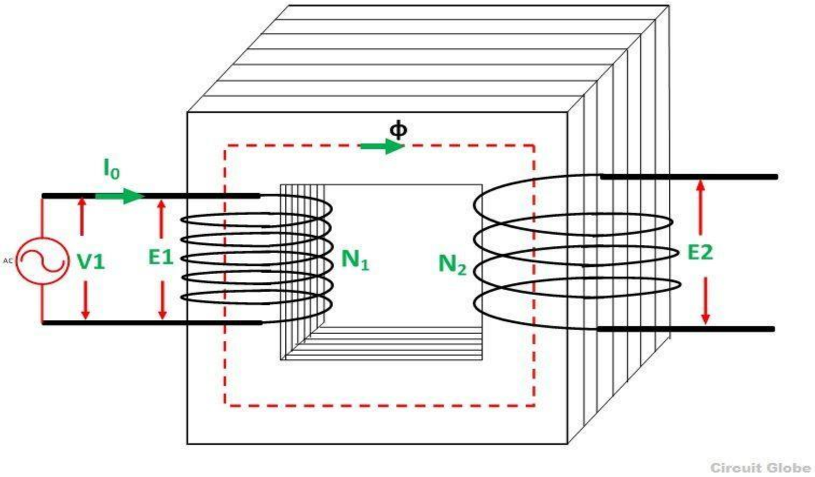
- Source Voltage $V_1 = V_{1'} + r_1I_e + jI_eX_1$, phasor sum. Thus the complete phasor diagram of transformer at no load will be as shown below.



Phasor Diagram of Transformer for Load Condition:

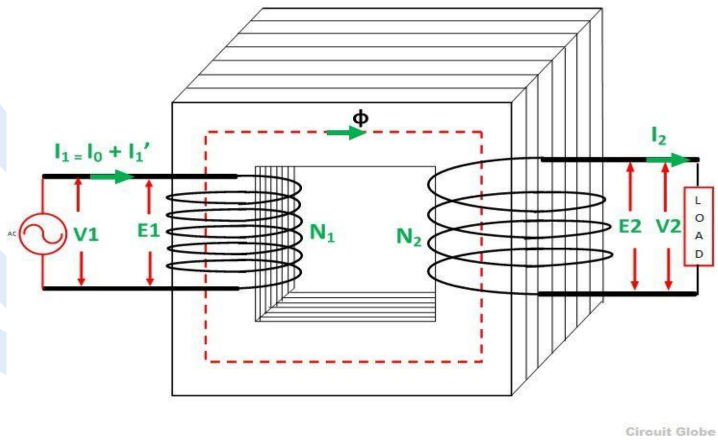
The Operation of the Transformer on Load Condition is explained below:

- When the secondary of the transformer is kept open, it draws the no-load current from the main supply. The no-load current induces the magnetomotive force N_0I_0 and this force set up the flux Φ in the core of the transformer. The circuit of the transformer at no load condition is shown in the figure below:



- When the load is connected to the secondary of the transformer, I_2 current flows through their secondary winding. The secondary current induces the magnetomotive force N_2I_2 on the secondary winding of the transformer. This force set up the flux φ_2 in the transformer core. The flux φ_2 opposes the flux φ, according to **Lenz's law**.

○



○

- As the flux φ_2 opposes the flux φ, the resultant flux of the transformer decreases and this flux reduces the induced EMF E_1. Thus, the strength of the V_1 is more than E_1 and an additional primary current I'_1 drawn from the main supply. The additional current is used for restoring the original value of the flux in the core of the transformer so that $V_1 = E_1$. The primary current I'_1 is in phase opposition with the secondary current I_2. Thus, it is called the **primary counter-balancing current**.

- The additional current I'_1 induces the magnetomotive force $N_1I'_1$. And this force set up the flux φ'_1. The direction of the flux is the same as that of the φ and it cancels the flux φ_2 which induces because of the MMF N_2I_2

Now, $N_1I_1' = N_2I_2$

Therefore,

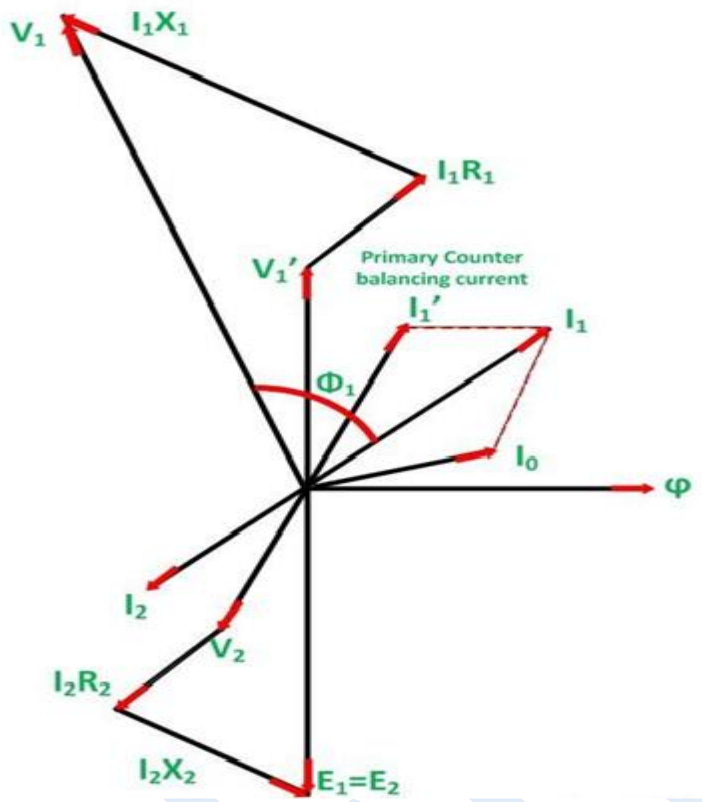
$$I_1' = \left(\frac{N_2}{N_1}\right) I_2 = KI_2$$

- The phase difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.
- If the load is inductive as shown in the above phasor diagram, the power factor will be lagging, and if the load is capacitive, the power factor will be leading. The total primary current I_1 is the vector sum of the currents I_0 and I_1'. i.e

$$\overline{I_1} = \overline{I_0} + \overline{I_1'}$$

Phasor Diagram of Transformer on Inductive Load

The phasor diagram of the actual transformer when it is loaded inductively is shown below:



Phasor Diagram of the Transformer on Inductive Load

Steps to draw the phasor diagram

- Take flux ϕ, a reference
- Induces emf E_1 and E_2 lags the flux by 90 degrees.
- The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding. E_1 is represented by V_1'.
- Current I_0 lags the voltage V_1' by 90 degrees.
- The power factor of the load is lagging. Therefore current I_2 is drawn lagging E_2 by an angle ϕ_2.
- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V_2 is the phase difference of E_2 and voltage drop.

$V_2 = E_2$ – voltage drops

$I_2 R_2$ is in phase with I_2 and I_2X_2 is in quadrature with I_2.

- The total current flowing in the primary winding is the phasor sum of I_1' and I_0.
- Primary applied voltage V_1 is the phasor sum of V_1' and the voltage drop in the primary winding.
- Current I_1' is drawn equal and opposite to the current I_2

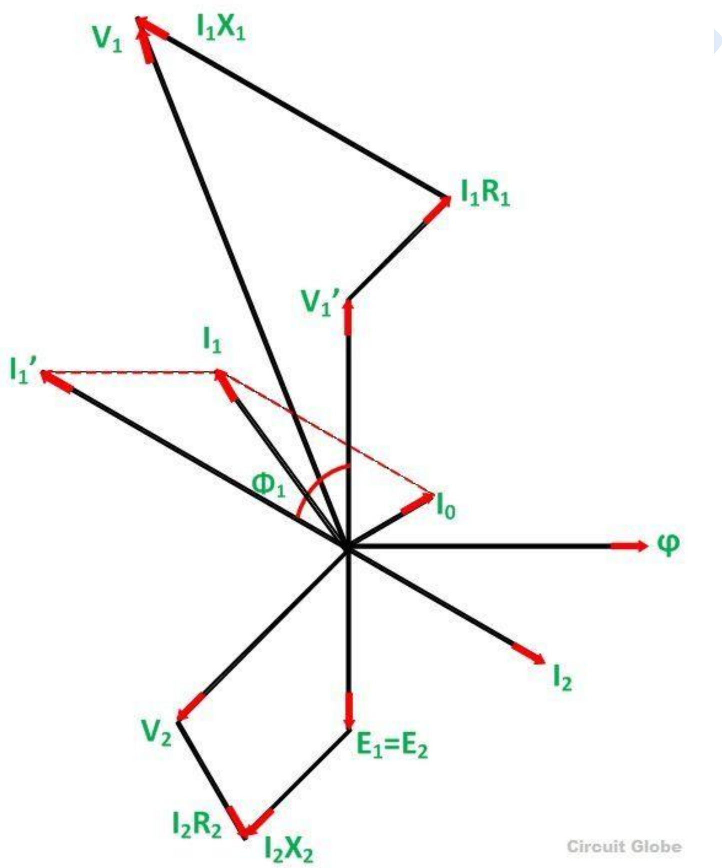
$V_1 = V_1' +$ voltage drop

I_1R_1 is in phase with I_1 and I_1X_I is in quadrature with I_1.

- The phasor difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.
- If the load is inductive as shown in the above phasor diagram, the power factor will be lagging, and if the load is capacitive, the power factor will be leading. Where I_1R_1 is the resistive drop in the primary windings
- I_2X_2 is the reactive drop in the secondary winding

Phasor Diagram of Transformer on Capacitive Load

The Transformer on the Capacitive load (leading power factor load) is shown below in the phasor diagram.



Phasor Diagram of the Transformer on Capacitive Load

Steps to draw the phasor diagram at capacitive load

- Take flux ϕ a reference
- Induces emf E_1 and E_2 lags the flux by 90 degrees.
- The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding. E_1 is represented by V_1'.
- Current I_0 lags the voltage V_1' by 90 degrees.
- The power factor of the load is leading. Therefore current I_2 is drawn leading E_2
- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V_2 is the phasor difference of E_2 and voltage drop.

$V_2 = E_2$ – voltage drops

$I_2 R_2$ is in phase with I_2 and I_2X_2 is in quadrature with I_2.

- Current I_1' is drawn equal and opposite to the current I_2
- The total current I_1 flowing in the primary winding is the phasor sum of I_1' and I_0.
- Primary applied voltage V_1 is the phasor sum of V_1' and the voltage drop in the primary winding.

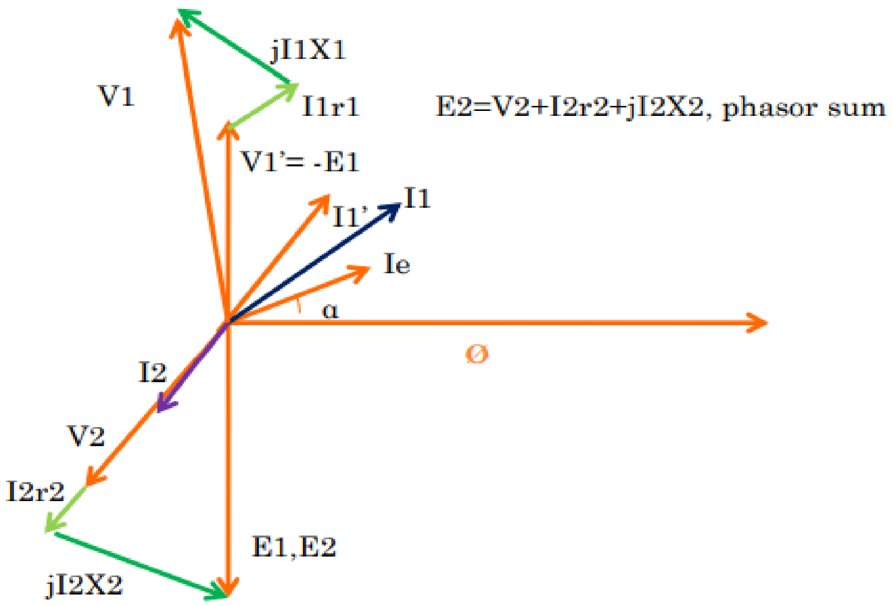
$V_1 = V_1$' + voltage drop

I_1R_1 is in phase with I_1 and I_1X_I is in quadrature with I_1.

- The phasor difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.

Phasor Diagram of Transformer on Resistive Load

For Resistive Load, load current will be in phase with the load Voltage V2.



OPEN CIRCUIT AND SHORT CIRCUIT TEST OF TRANSFORMERS

Open circuit test and short circuit test are conducted to determine the core loss, copper loss, and equivalent circuit parameters of a transformer.

Normally transformers are tested at no-load. Transformers can be tested by connecting load to its secondary if its rating is small. In the case of large transformers, it is exceedingly difficult to arrange large loads enough for direct loading. Also, load tests are associated with a large amount of power wastage. Hence it is preferred to test transformers without load.

Why is it necessary to conduct OC and SC tests?

It is necessary to know the impedance of the transformer in order to calculate its voltage regulation and efficiency. The impedance and other circuit parameters can be determined by conducting simple no-load tests. No-load tests have a minimal power loss when compared to that during direct load tests.

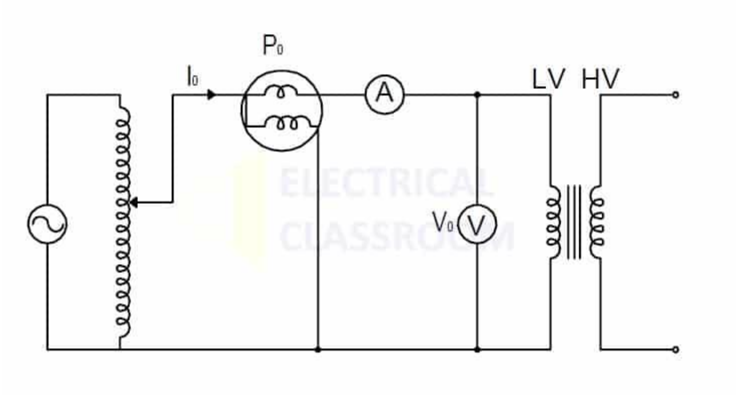
The input voltage, current, and power are measured and based on that the equivalent circuit parameters can be determined.

OPEN CIRCUIT TEST

The open circuit test is performed to determine the no load losses or core losses as well as the turns ratio, no load currents, magnetizing components and core loss components of the transformer.

Circuit for open circuit test

For convenience, the supply is connected to the LV side of the transformer and the HV side of the transformer is left open. Voltmeters, ammeters and watt meter are connected as shown in the figure below.

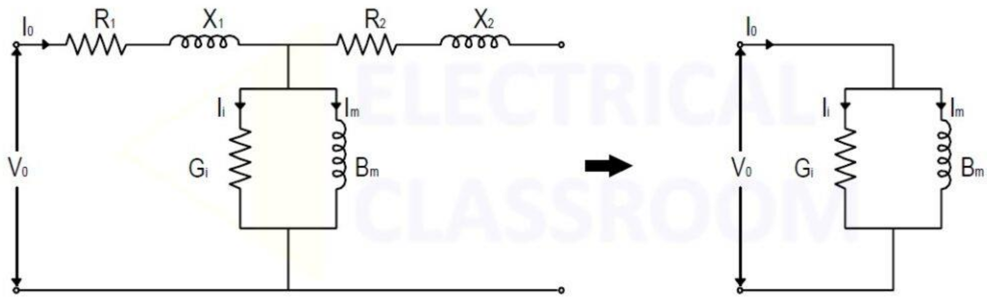


Circuit for open circuit test

Open circuit test Procedure

- Apply rated voltage to the LV side of the transformer.
- Measure the no-load current Io, power P_o, and input voltage V_o.
- Measure the open-circuited HV side voltage if the transformer ratio needs to be calculated.

Calculation of core losses and magnetizing components



As no load is connected to the secondary, the current flow and the losses due to winding resistance and reactance are very less and can be neglected and the circuit is simplified.

Neglecting the copper loss, we calculate the core losses and the core loss components.

$$P_o = V_o.I_o.Cos\phi$$

$$Cos\phi = \frac{P_o}{V_o.I_o}$$

$$I_m = I_o.Sin\phi$$

$$I_i = I_o.Cos\phi$$

Where, I_m is the magnetizing current and I_i is the core loss component.

Core admittance,

$$Y_o = G_i + jB_m = \sqrt{G_i^2 + B_m^2}$$

Also,

$$Y_o = \frac{I_o}{V_o}$$

The conductivity of the core,

$$G_i = \frac{P_o}{V_o^2}$$

The Susceptance of the core,

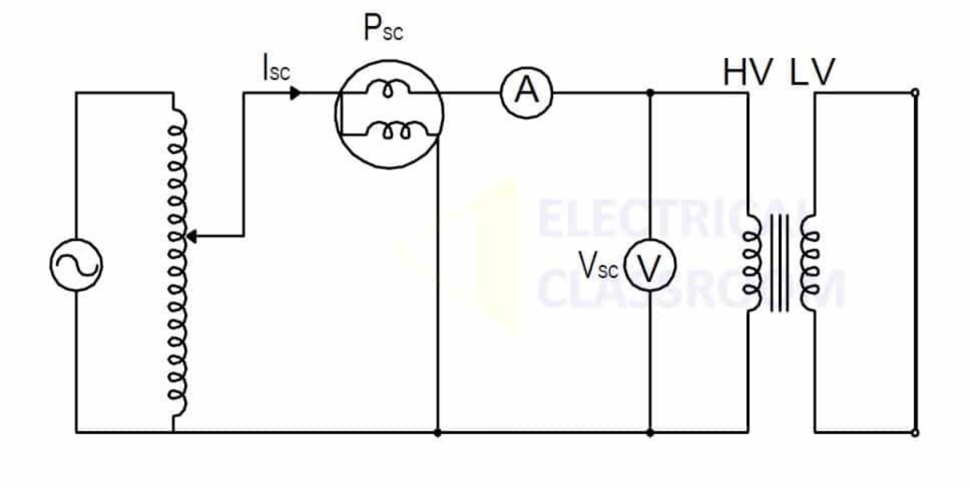
$$B_m = \sqrt{Y_o^2 - G_i^2}$$

Where Y_0 is the core admittance, G_i is the conductivity of the core, B_m is the Susceptance of the core.

SHORT CIRCUIT TEST

The purpose of conducting a short circuit test is to determine the winding resistance, reactance, and the copper loss of the transformer.

Circuit for short circuit test

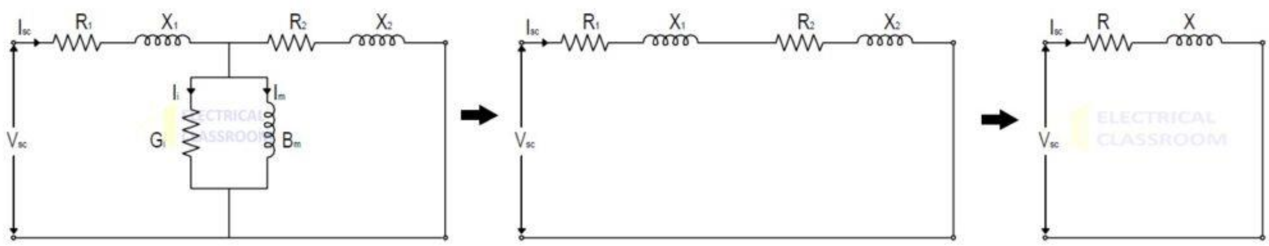


For convenience a variable voltage source is connected to the HV side of the transformer and the LV side of the transformer is short circuited. This is because, the voltage required for short circuit test is typically 5 per cent of the rated value. Since the current rating of HV is less than the LV, the current drawn at 5 per cent of rated voltage of HV is low. At the same time, if we apply voltage to LV winding, the current drawn from the supply will be very high. It is difficult to arrange a low voltage – high current power source.

Short circuit test Procedure

- Gradually raise the supply voltage from zero, until the transformer draws its rated current.
- Note down the voltmeter readings V_{sc}, wattmeter reading P_{sc}, and ammeter reading I_{sc}.

It can be noted that the applied voltage, V_{sc}, required to circulate current I_{sc} is very small compared to the rated voltage of the winding (typically 5% of rated voltage). Therefore, the excitation current required is too small and can be neglected.



Where R = $R_1 + R_2$ and X = $X_1 + X_2$

The power input to the transformer measured by P_{sc} corresponds to copper loss. Therefore

$$P_{sc} = P_{I^2R}$$

$$V_{sc} = I_{sc}.Z$$

Where,

$$Z = R + jX = \frac{V_{sc}}{I_{sc}}$$

The resistance offered by the coil,

$$R = \frac{P_{sc}}{I_{sc}^2}$$

The Susceptance of the core,

$$X = \sqrt{Z^2 - R^2}$$

The attained values of R and X are referred to the HV side of the transformer from which the test is conducted. If can be referred to the other side using the operator a^2 (square of turns ratio).

Calculation of transformer efficiency

If P_0 and P_{sc} are the core loss and the copper loss of a transformer respectively, the efficiency of the transformer can be calculated using the following formula:

$$\% Efficiency, \mu = \frac{kVA\, rating\, of\, transformer}{kVA\, rating\, of\, transformer + P_0 + P_{sc}} \times 100\%$$

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

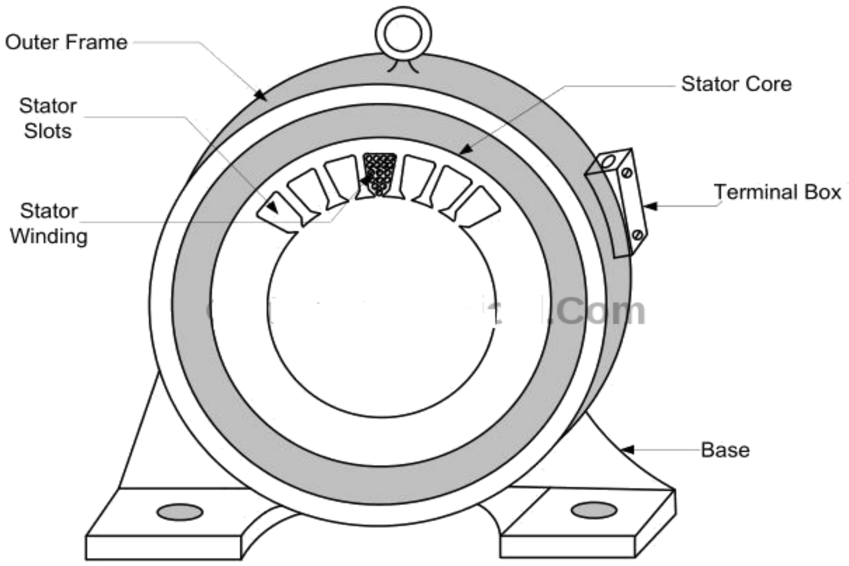
1. **Stator**
2. **Rotor**

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.

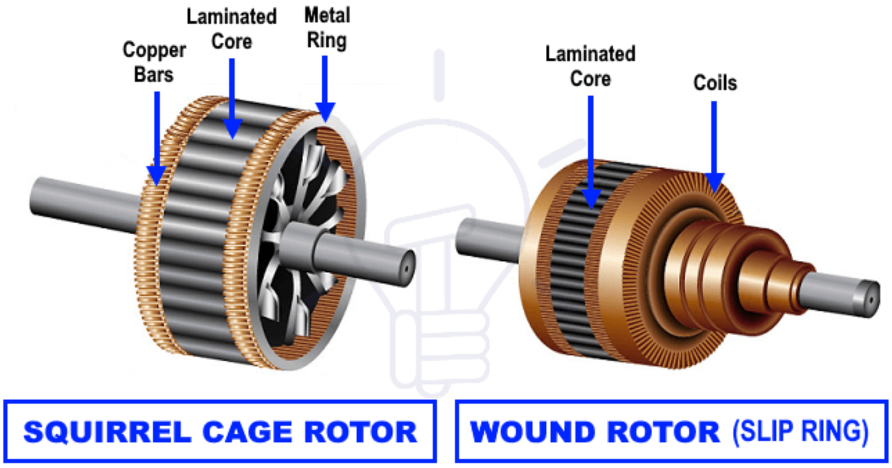
According to the application and type of starting methods of motors, the stator winding is connected in star or delta and it is done by the connection of terminals in the terminal box.

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.

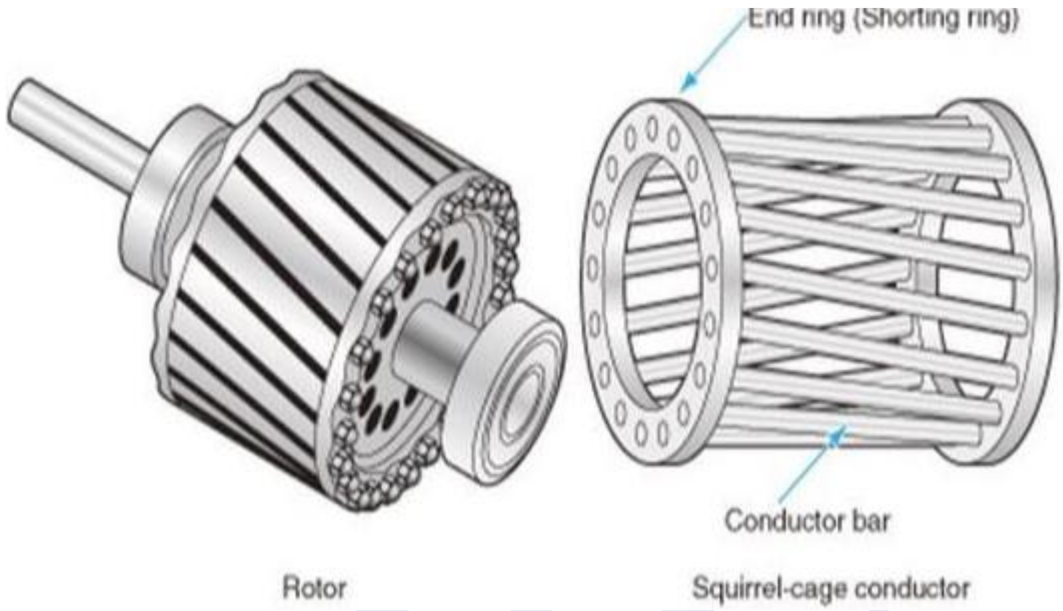
The rotor consists of a cylindrical laminated core and has slots on the outer periphery. The slots are not parallel but it is skewed at some angle. It helps to prevent magnetic locking between the stator and rotor teeth. It results in smooth operation and reduces the humming noise. It increases the length 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

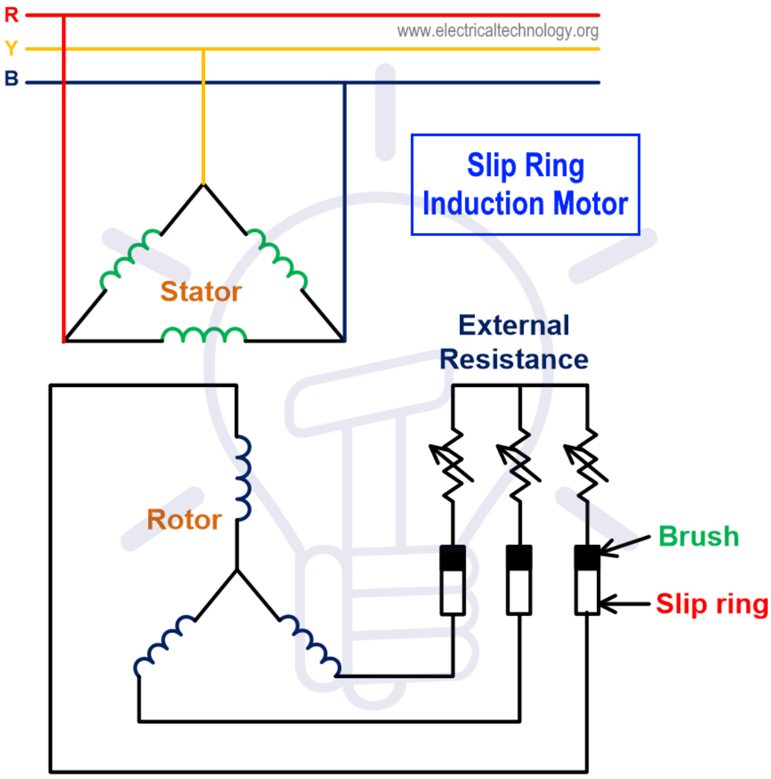
Slip-ring induction motors are also known as wound rotor motor. The rotor consists of a laminated cylindrical core with slots on the outer periphery. The rotor winding is placed inside the slots.

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

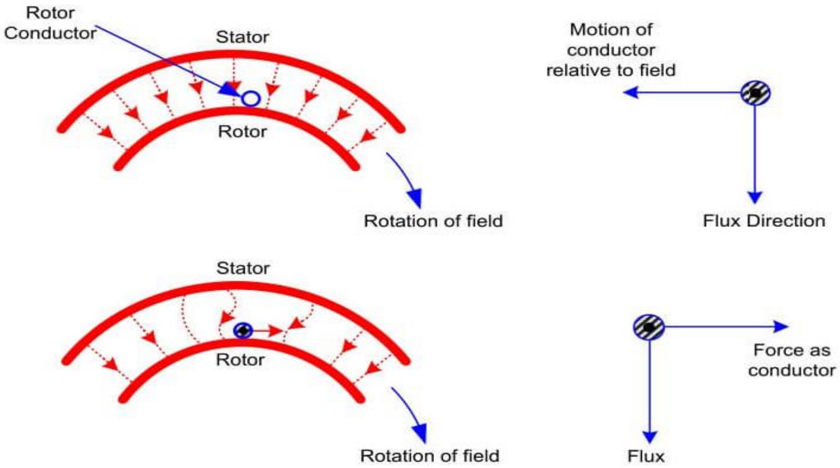
- Compressor
- And other low mechanical power applications

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

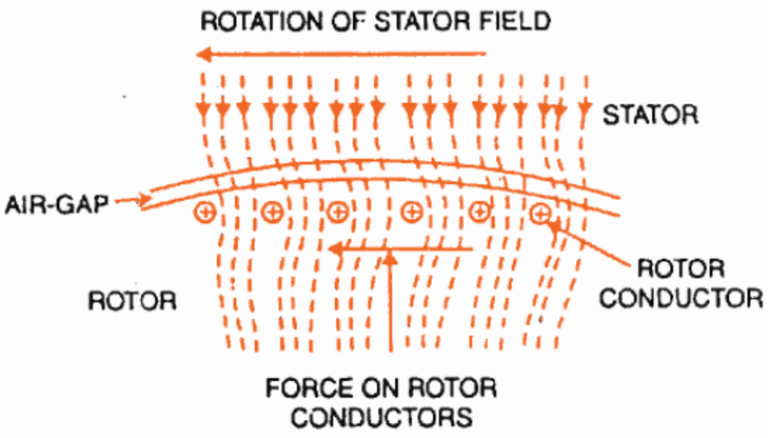
WORKING PRINCIPLE THREE PHASE INDUCTION MOTOR

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**.

Why the slip is never zero in an induction motor?

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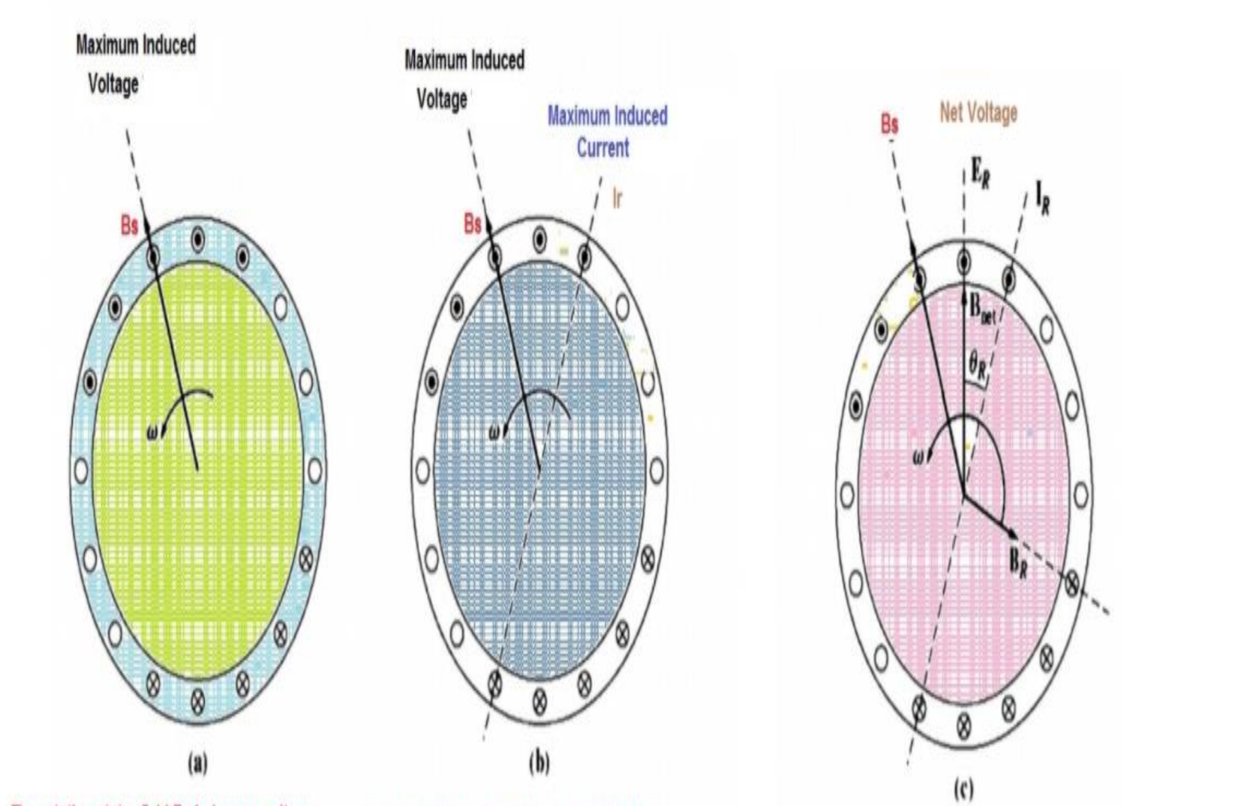
Because when the slip is zero, both speeds are equal and there is no relative motion. Therefore, no EMF induced in the rotor circuit and rotor current is zero. Hence, the motor cannot run.

Development of Induced Torque in a Three Phase Induction Motor

- In a given diagram we can see that the cage rotor of three-phase induction motor.
- At this rotor, we have supplied 3-phase inputs at stating part of the motor and we can see that 3-currents moving in the stator.



(a) The rotating stator field Bs induces a voltage in the rotor bars

(b) rotor voltage produces a rotor current flow, which lags behind the voltage because of the inductance of the rotor

(c) the rotor current produces a rotor magnetic field BR lagging 90° behind itself. and BR interacts with Bnet to produce a counterclockwise torque in the machine.

- These 3 currents create a rotating magnetic field (Bs) which is revolving in an anticlockwise direction.
- The speed of this rotating magnetic field can be measured by the given formula.

$$\mathbf{n_{sync} = 120f/p}$$

- In this equation.
  - n_{sync} shows the speed of the rotating magnetic field.
  - f is the frequency of the system.
  - (P) is no of the pole in the motor.
- The revolving field (Bs) when linked with the rotor then it induce emf in the rotor which is explained as.

$$\mathbf{e_{ind} = (v \times B) \times I}$$

- In this equation:
  - V is the rotation of the rotor with respect to the field.

  - B is the rotating magnetic field.
  - L is the length of the rotor (we can say that it is the length of bars in the field).
- It is the comparative motion of the rotor associated with the magnetic field which induced a voltage on the bars of the rotor.
- The direction of the Speed of rotor bars which are located on top is ninety degrees to the magnetic field which causes to generate emf in these bars out of the page, but in lower bars the direction of emf induced in the page.
- Though, as the rotor assemblage has inductive properties, the highest rotor current (I) lags the highest rotor voltage (V).
- The current moving in the rotor causes to generate a rotor magnetic field which is denoted as B_R.

$$\mathbf{T_{ind} = kB_R \times Bs}$$

- It is the induced torque in the motor.
- The resultant torque is in an anticlockwise direction. The rotation direction of the rotor depends on the direction of induced torque, as torque direction is anticlockwise, so the rotor also moves in an anticlockwise direction.
- There is a fixed higher limit to the speed of a motor, but. If the rotor of the motor is moving on the synchronous speed, so bars of the rotor would be static with respect to the field and there will be no emf induced in the rotor.
- If induced emf is zero, then there will be no current in the rotor and no field.

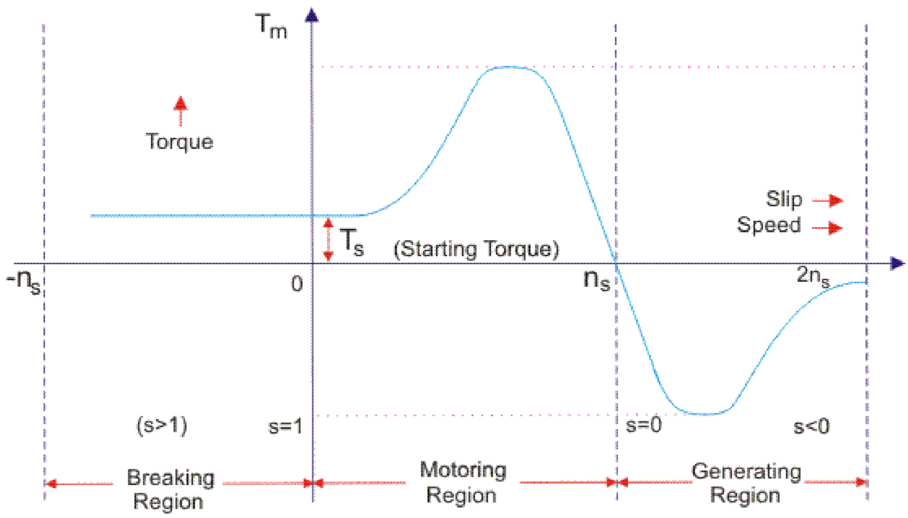
$$\mathbf{T_{ind} = kB_R \times Bs}$$

- In this above equation, we can see that torque also depends on the rotor's emf if there is no rotor emf then there will be no torque, so the motor will slow down and stops working.

TORQUE SLIP CHARACTERISTICS OF THREE PHASE INDUCTION MOTOR

The torque slip curve for an induction motor gives us the information about the variation of torque with the slip. The slip is defined as the ratio of difference of synchronous speed and actual rotor speed to the synchronous speed of the machine. The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary.

The curve can be described in three modes of operation-



Torque Slip Curve for Three Phase Induction Motor

The torque-slip characteristic curve can be divided roughly into three regions:

- Low slip region
- Medium slip region
- High slip region

Motoring Mode

In this mode of operation, supply is given to the stator sides and the motor always rotates below the synchronous speed. The **induction motor torque** varies from zero to full load torque as the slip varies. The slip varies from zero to one. It is zero at no load and one at standstill. From the curve it is seen that the torque is directly proportional to the slip. That is, more is the slip, more will be the torque produced and vice-versa. The linear relationship simplifies the calculation of motor parameter to great extent.

Generating Mode

In this mode of operation induction motor runs above the synchronous speed and it should be driven by a prime mover. The stator winding is connected to a three phase supply in which it supplies electrical energy. Actually, in this case, the torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy. Induction motor is not much used as generator because it requires reactive power for its operation. That is, reactive power should be supplied from outside and if it runs below the synchronous speed by any means, it consumes electrical energy rather than giving it at the output. So, as far as possible, induction generators are generally avoided.

Braking Mode

In the Braking mode, the two leads or the polarity of the supply voltage is changed so that the motor starts to rotate in the reverse direction and as a result the motor stops. This method of braking is known as plugging. This method is used when it is required to stop the motor within a very short period of time. The kinetic energy stored in the revolving load is dissipated as heat. Also, motor is still receiving power from the stator which is also dissipated as heat. So as a result of which motor develops enormous heat energy. For this stator is disconnected from the supply before motor enters the braking mode.

If load which the motor drives accelerates the motor in the same direction as the motor is rotating, the speed of the motor may increase more than synchronous speed. In this case, it acts as an induction generator which supplies electrical energy to the mains which tends to slow down the motor to its synchronous speed, in this case the motor stops. This type of breaking principle is called dynamic or regenerative breaking.

STARTING METHODS OF THREE PHASE INDUCTION MOTORS

An induction motor is similar to a poly-phase transformer whose secondary is short circuited. Thus, at normal supply voltage, like in transformers, the initial current taken by the primary is very large for a short while. Unlike in DC motors, large current at starting is due to the absence of back emf. If an induction motor is directly switched on from the supply, it takes 5 to 7 times its full load current and develops a torque which is only 1.5 to 2.5 times the full load torque. This large starting current produces a large voltage drop in the line, which may affect the operation of other devices connected to the same line. Hence, it is not advisable to start induction motors of higher ratings (generally above 25kW) directly from the mains supply.
Various **starting methods of induction motors** are described below.

Direct-On-Line (DOL) Starters

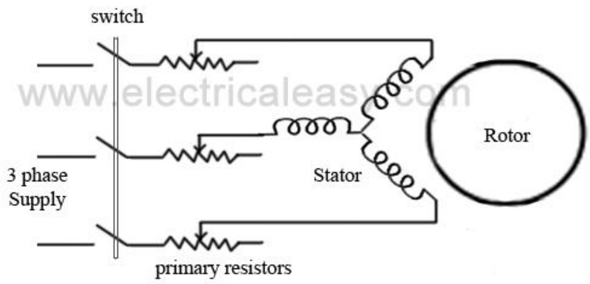
Small three phase induction motors can be started direct-on-line, which means that the rated supply is directly applied to the motor. But, as mentioned above, here, the starting current would be very large, usually 5 to 7 times the rated current. The starting torque is likely to be 1.5 to 2.5 times the full load torque. Induction motors can be started directly on-line using a DOL starter which generally consists of a contactor and a motor protection equipment such as a circuit breaker. A DOL starter consists of a coil operated contactor which can be controlled by start and stop push buttons. When the start push button is pressed, the contactor gets energized and it closes all the three phases of the motor to the supply phases at a time. The stop push button de-energizes the contactor and disconnects all the three phases to stop the motor. In order to avoid excessive voltage drop in the supply line due to large starting current, a DOL starter is generally used for motors that are rated below 5kW.

Starting Of Squirrel Cage Motors

Starting in-rush current in squirrel cage motors is controlled by applying reduced voltage to the stator. These methods are sometimes called as **reduced voltage methods for starting of squirrel cage induction motors**. For this purpose, following methods are used:

1. By using primary resistors
2. Autotransformer
3. Star-delta switches

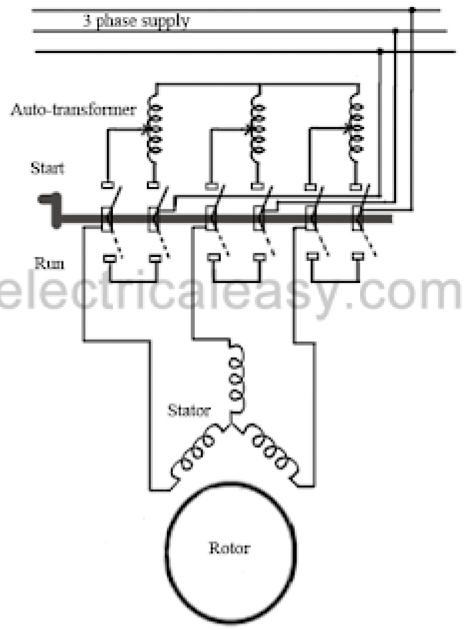
1. Using Primary Resistors:



Obviously, the purpose of primary resistors is to drop some voltage and apply a reduced voltage to the stator. Consider, the starting voltage is reduced by 50%. Then according to the Ohm's law (V=I/Z), the starting current will also be reduced by the same percentage. From the torque equation of a three phase induction motor, the starting torque is approximately proportional to the square of the applied voltage. That means, if the applied voltage is 50% of the rated value, the starting torque will be only 25% of its normal voltage value. This method is generally used for a **smooth starting of small induction motors**. It is not recommended to use primary resistors type of starting method for motors with high starting torque requirements.

Resistors are generally selected so that 70% of the rated voltage can be applied to the motor. At the time of starting, full resistance is connected in the series with the stator winding and it is gradually decreased as the motor speeds up. When the motor reaches an appropriate speed, the resistances are disconnected from the circuit and the stator phases are directly connected to the supply lines.

2. Auto-Transformers:



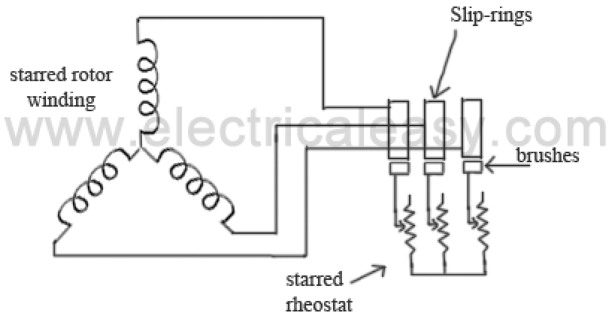
Auto-transformers are also known as auto-starters. They can be used for both star connected or delta connected squirrel cage motors. It is basically a three phase step down transformer with different taps provided that permit the user to start the motor at, say, 50%, 65% or 80% of line voltage. With auto-transformer starting, the current drawn from supply line is always less than the motor current by an amount equal to the transformation ratio. For example, when a motor is started on a 65% tap, the applied voltage to the motor will be 65% of the line voltage and the applied current will be 65% of the line voltage starting value, while the line current will be 65% of 65% (i.e. 42%) of the line voltage starting value. This difference between the line current and the motor current is due to transformer action. The internal connections of an auto-starter are as shown in the figure. At starting, switch is at "start" position, and a reduced voltage (which is selected using a tap) is applied across the stator. When the motor gathers an appropriate speed, say upto 80% of its rated speed, the auto-transformer automatically gets disconnected from the circuit as the switch goes to "run" position.

The switch changing the connection from start to run position may be air-break (small motors) or oil-immersed (large motors) type. There are also provisions for no-voltage and overload, with time delay circuits on an autostarter.

3. Star-Delta Starter:

This method is used in the motors, which are designed to run on delta connected stator. A two way switch is used to connect the stator winding in star while starting and in delta while running at normal speed. When the stator winding is star connected, voltage over each phase in motor will be reduced by a factor 1/(sqrt. 3) of that would be for delta connected winding. The starting torque will 1/3 times that it will be for delta connected winding. Hence a star-delta starter is equivalent to an auto-transformer of ratio 1/(sqrt. 3) or 58% reduced voltage.

Starting Of Slip-Ring Motors



Phase wound rotor connections

Slip-ring motors are started with full line voltage, as external resistance can be easily added in the rotor circuit with the help of slip-rings. A star connected rheostat is connected in series with the rotor via slip-rings as shown in the fig. Introducing resistance in rotor current will decrease the starting current in rotor (and, hence, in stator). Also, it improves power factor and the torque is increased. The connected rheostat may be hand-operated or automatic.
As, introduction of additional resistance in rotor improves the starting torque, slip-ring motors can be started on load.

The external resistance introduced is only for starting purposes, and is gradually cut out as the motor gathers the speed.

CONCEPT OF ROTATING MAGNETIC FIELD

The fundamental principle of operation of AC machines is the **generation of a rotating magnetic field**, which causes the rotor to turn at a speed that depends on the speed of rotation of the magnetic field.

We'll now explain ***how a rotating magnetic field can be generated in the stator*** *and air gap of an AC machine by means of alternating currents.*

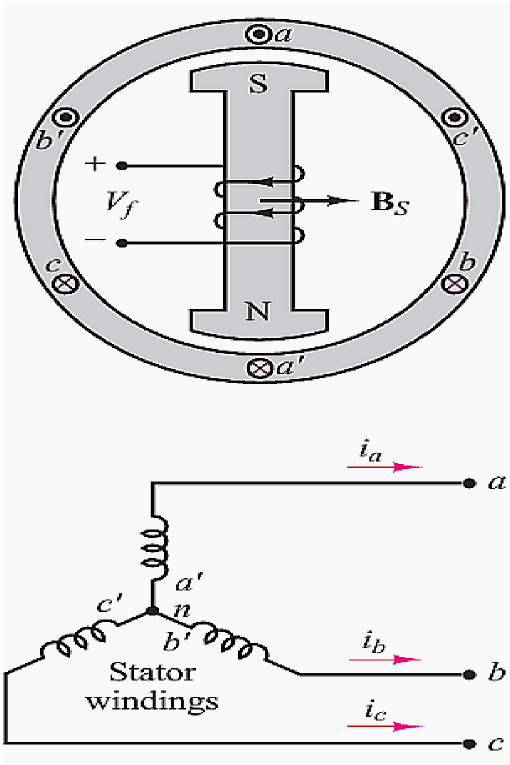


Figure – Two-pole three-phase stator

Consider the stator shown in Figure 1, which supports **windings a-a′, b-b′ and c-c′**. The coils are geometrically spaced 120◦ apart, and a three-phase voltage is applied to the coils. The currents generated by a three-phase source are also spaced by 120◦, as illustrated in Figure 2 below.

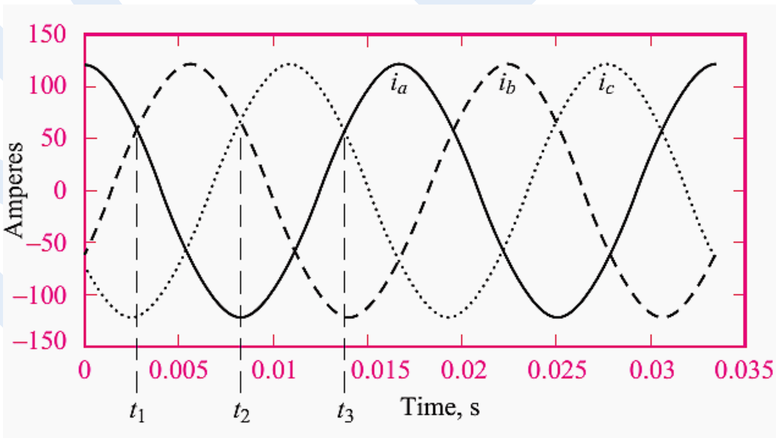


Figure – Three-phase stator winding currents

The phase voltages referenced to the neutral terminal would then be given by the expressions //

$$v_a = A\cos(\omega_e t)$$
$$v_b = A\cos\left(\omega_e t - \frac{2\pi}{3}\right)$$
$$v_c = A\cos\left(\omega_e t + \frac{2\pi}{3}\right)$$

where $\boldsymbol{\omega_e}$ is the frequency of the AC supply, or line frequency. The coils in each winding are arranged in such a way that the flux distribution generated by any one winding is approximately sinusoidal.

Such a flux distribution may be obtained by appropriately **arranging groups of coils for each winding over the stator surface**. Since the coils are spaced 120° apart, the flux distribution resulting from the sum of the contributions of the three windings is the sum of the fluxes due to the separate windings, as shown in Figure 3.

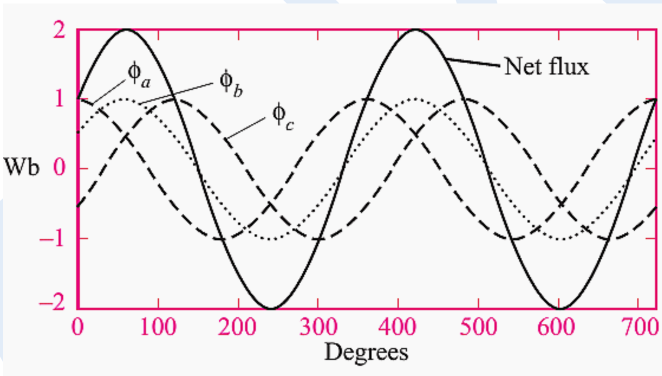


Figure – Flux distribution in a three-phase stator winding as a function of angle of rotation

Thus, the flux in a three-phase machine rotates in space according to the vector diagram of Figure 4, and the flux is constant in amplitude. A stationary observer on the machine's stator would see a **sinusoidally varying flux distribution**, as shown in Figure 3.

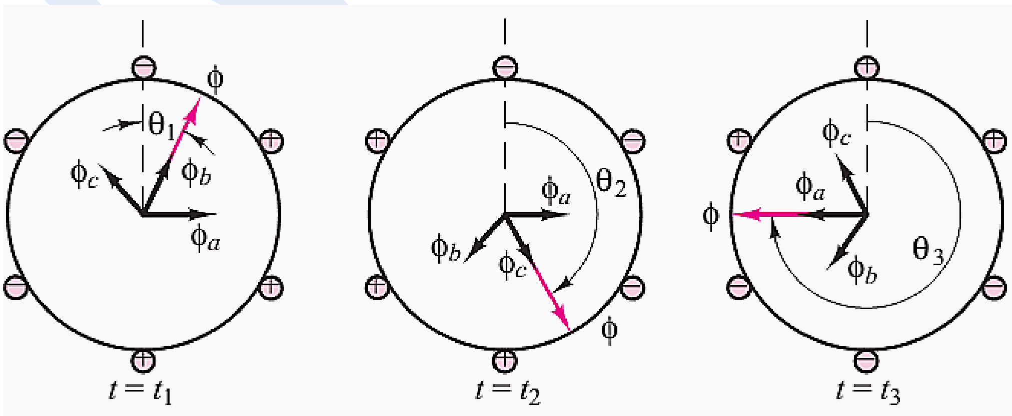


Figure – Rotating flux in a three-phase machine

Since the resultant flux of Figure 3 is generated by the currents of Figure 2, the speed of rotation of the flux must be related to the frequency of the sinusoidal phase currents. In the case of the stator of Figure 1, the number of magnetic poles resulting from the winding configuration is 2.

However, it is also possible to configure the windings ***so that they have more poles****. For example, Figure 5 depicts a simplified view of a four-pole stator.*

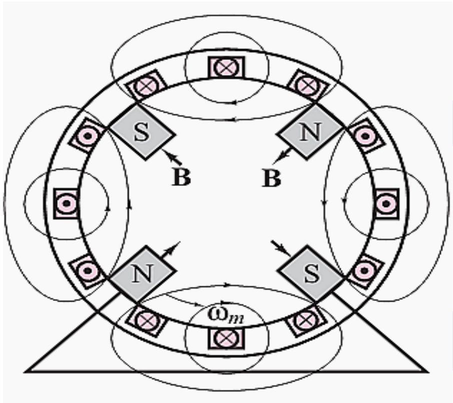


Figure – Four-pole stator

In general, the speed of the rotating magnetic field is determined by the frequency of the excitation current **f** and by the number of poles present in the stator **p** according to

$$n_s = \frac{120\,f}{p} \text{ r/min} \qquad \text{Synchronous speed}$$

$$\omega_s = \frac{2\pi\, n_S}{60} = \frac{2\pi \times 2f}{p} \qquad \text{Synchronous speed}$$

where $\mathbf{n_s}$ **(or** $\boldsymbol{\omega_s}$**)** is usually called the synchronous speed.

Now, the structure of the windings in the preceding discussion is the same whether the AC machine is a motor or a generator. The distinction between the two depends on the direction of power flow. In a generator, the electromagnetic torque is a reaction torque that opposes rotation of the machine; this is the torque against which the prime mover does work.

NOTE: *In a motor, on the other hand, the rotational (motional) voltage generated in the armature opposes the applied voltage. This voltage is the counter (or back) emf. Thus, the description of the rotating magnetic field given thus far applies to both motor and generator action in AC machines.*

As described aabove, the stator magnetic field rotates in an AC machine, and therefore the rotor cannot “catch up” with the stator field and is in constant pursuit of it.

The speed of rotation of the rotor will therefore depend on ***the number of magnetic poles present in the stator and in the rotor****.*

The magnitude of the torque produced in the machine is a function of the **angle γ** between the stator and rotor magnetic fields. Precise expressions for this torque depend on how the magnetic fields are generated and will be given separately for the two cases of synchronous and induction machines.

MODULE VI

SPECIAL ELECTRICAL MACHINES

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 $\Phi_m/2$.

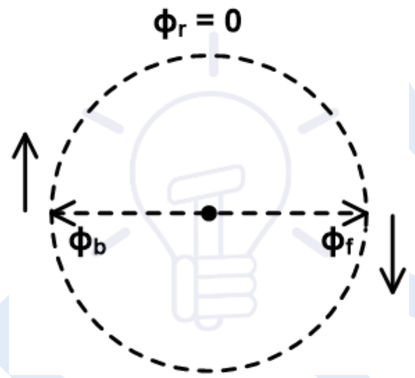
Out of these two fields, one field Φ_f is rotating in an anticlockwise direction and the second field Φ_b is rotating in a clockwise direction. Therefore, the resultant field is zero.

$$\Phi_r = \Phi_f - \Phi_b$$

$$\Phi_r = \frac{\Phi_m}{2} - \frac{\Phi_m}{2}$$

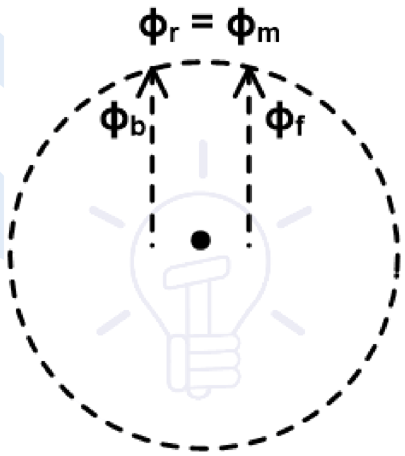
$$\mathbf{\Phi_r = 0}$$

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

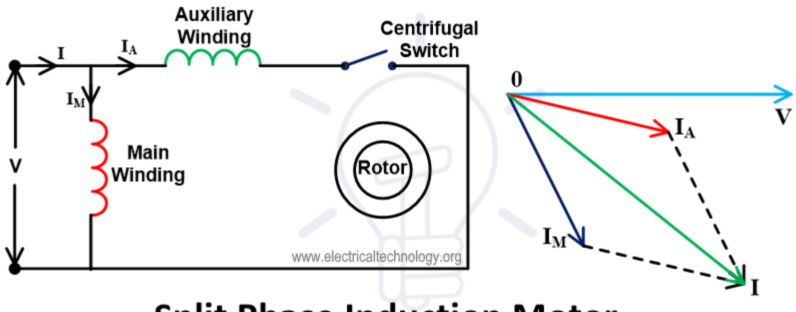
SPLIT PHASE INDUCTION MOTOR

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

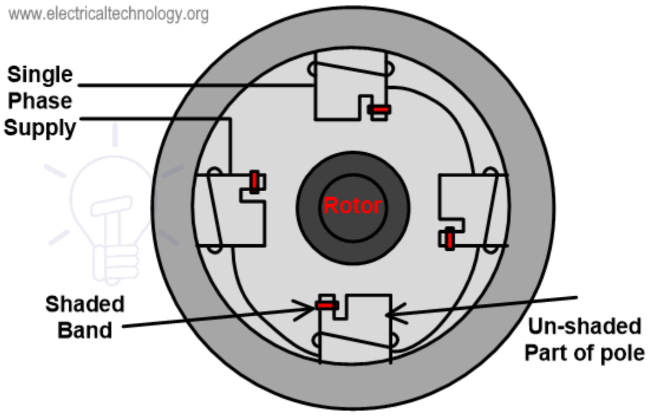
As compared to other types of single-phase induction motor, this motor has a different construction and working principle. This type of motor does not require auxiliary winding.

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.

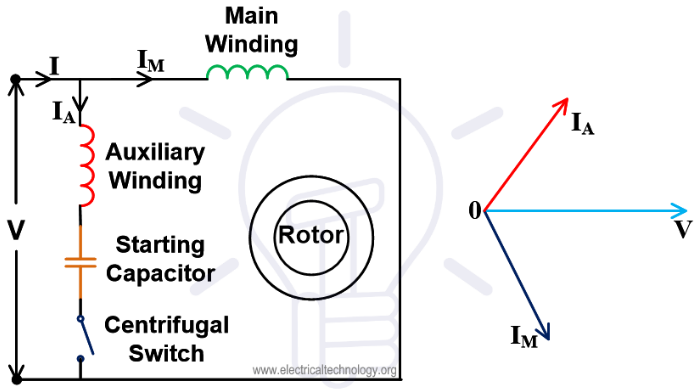
The shaded ring is a highly inductive coil. So, it will oppose the main flux when both fluxes are in the same direction and it will increase the main flux when both fluxes are in the opposite direction.

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.

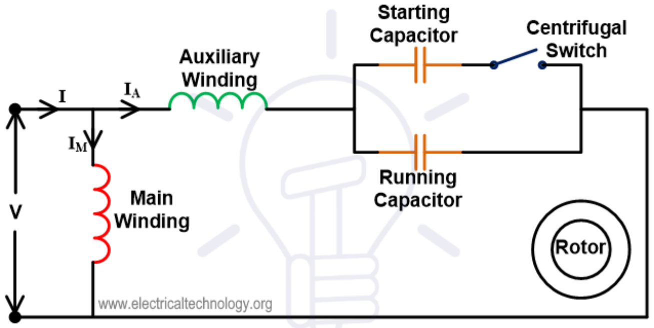
So, the starting torque of this motor is very high compared to the split-phase induction motor. The starting torque of this motor is 300% more than the full load torque.

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.

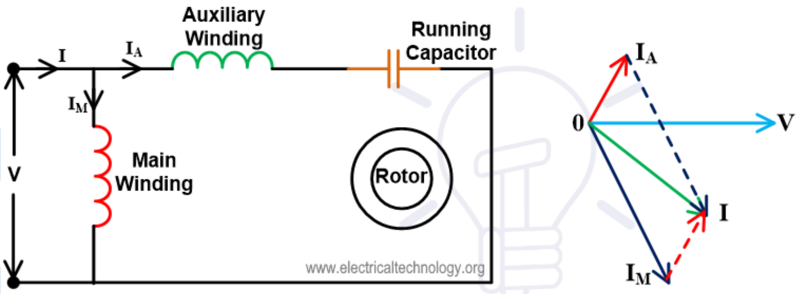
Therefore, this can be used in the application where high starting torque is required like a refrigerator, air conditioner, ceiling fan, compressor, etc.

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.

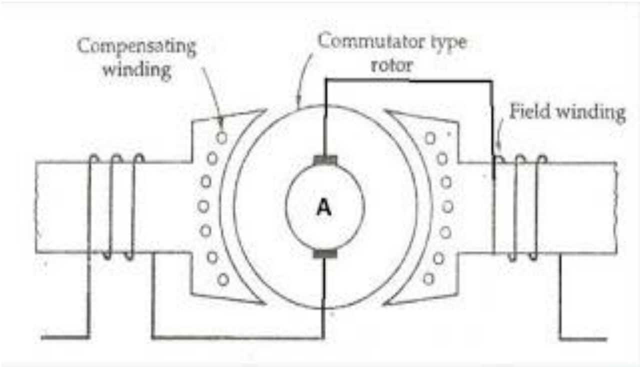
This motor is a commutator type motor.

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.

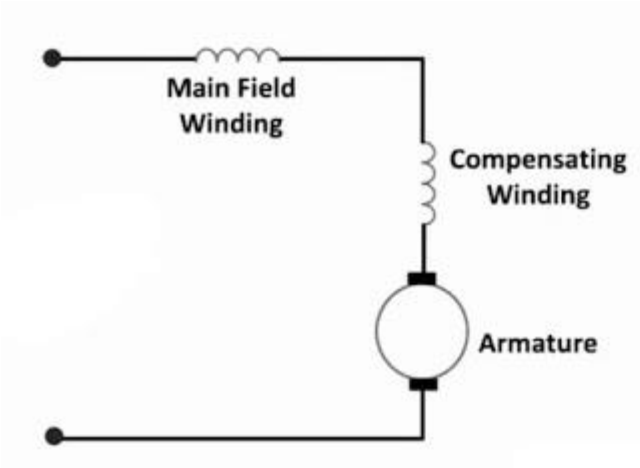
The armature is wound type same as small dc motor, it has laminated core having straight or skewed slots and commutator to which armature winding leads are connected.

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.

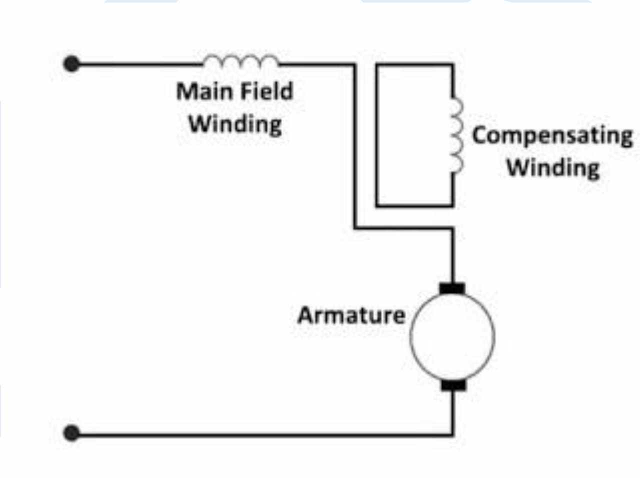
In compensated type motor, compensating winding is used to reduced reactance voltage drop in armature when it operated on AC supply. This voltage is caused by the transformer action due to alternating flux.

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.

STEPPER MOTOR

How a stepper motor works?

Stepper motors work on the principle of electromagnetism. There is a soft iron or magnetic rotor shaft surrounded by the electromagnetic stators. The rotor and stator have poles which may be teethed or not depending upon the type of stepper. When the stators are energized the rotor moves to align itself along with the stator (in case of a permanent magnet type stepper) or moves to have a minimum gap with the stator (in case of a variable reluctance stepper). This way the stators are energized in a sequence to rotate the stepper motor. Get more information about working of stepper motors through interesting images at the stepper motor Insight.

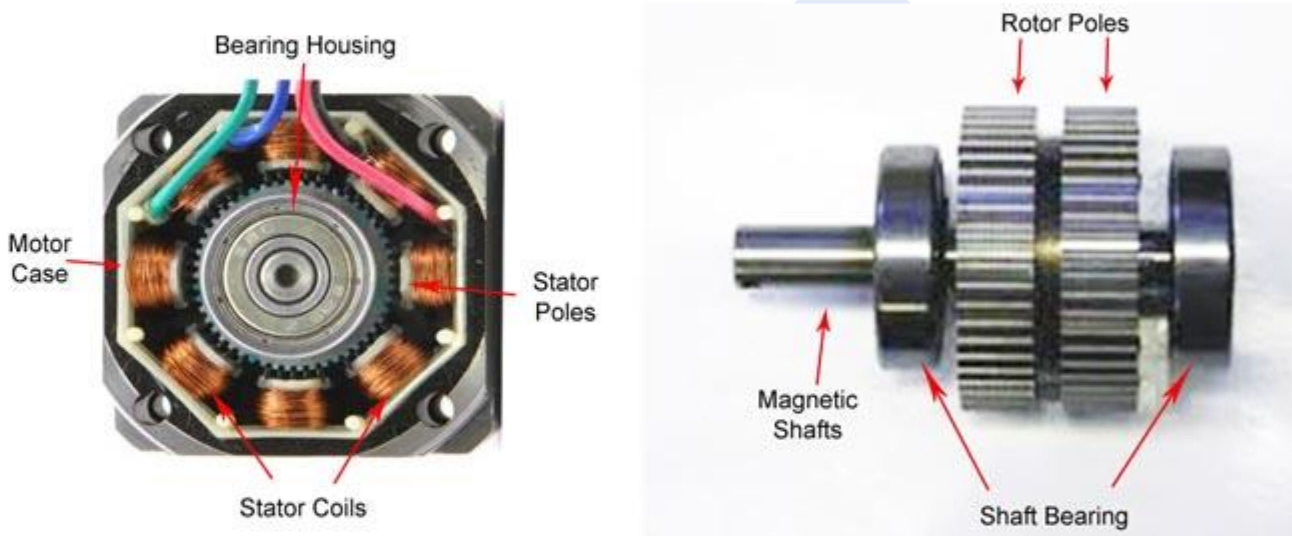


Fig. 2: General Overview Of Internal Structure And Working Of Typical Stepper Motor

TYPES OF STEPPER MOTOR

By construction the step motors come into three broad classes:

1. Permanent Magnet Stepper
2. Variable Reluctance Stepper
3. Hybrid Step Motor

1. Permanent Magnet Stepper :

The rotor and stator poles of a permanent magnet stepper are not teethed. Instead the rotor have alternative north and south poles parallel to the axis of the rotor shaft.

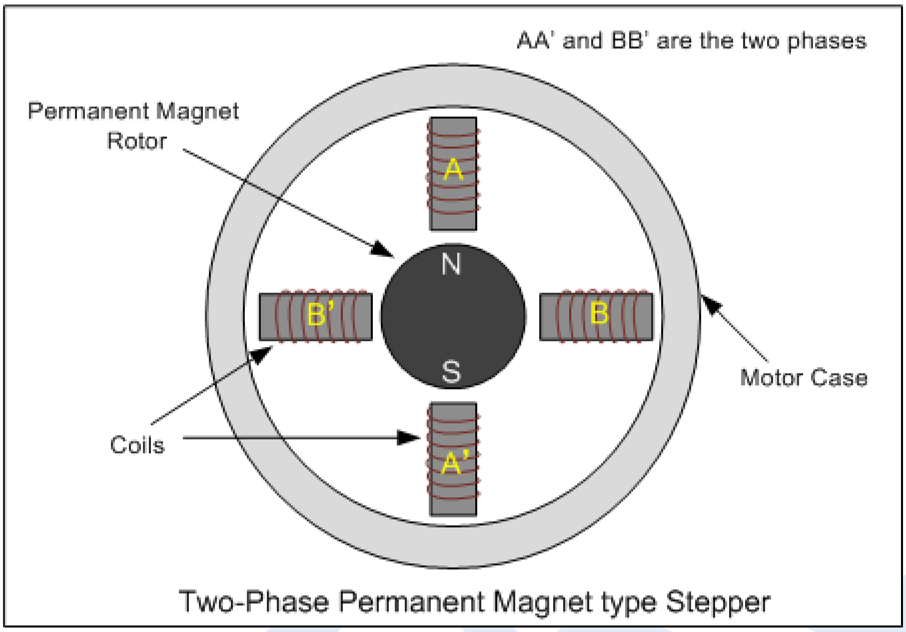


Fig. 3: Crossectional Diagram Of Two Phase Permanent Stepper Motor

When a stator is energized, it develops electromagnetic poles. The magnetic rotor aligns along the magnetic field of the stator. The other stator is then energized in the sequence so that the rotor moves and aligns itself to the new magnetic field. This way energizing the stators in a fixed sequence rotates the stepper motor by fixed angles.

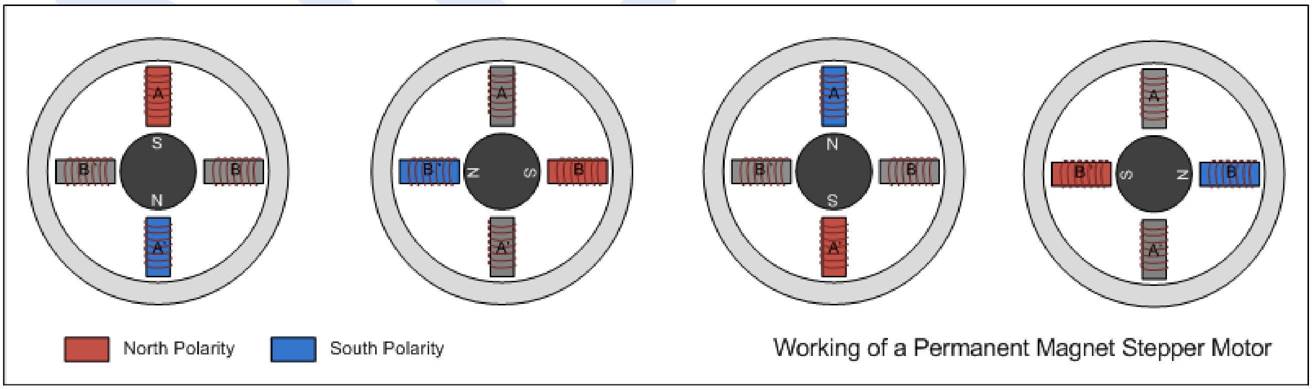


Fig. 4: Diagram Explaining Working Of Permanent Magnet Stepper Motor

The resolution of a permanent magnet stepper can be increased by increasing number of poles in the rotor or increasing the number of phases.

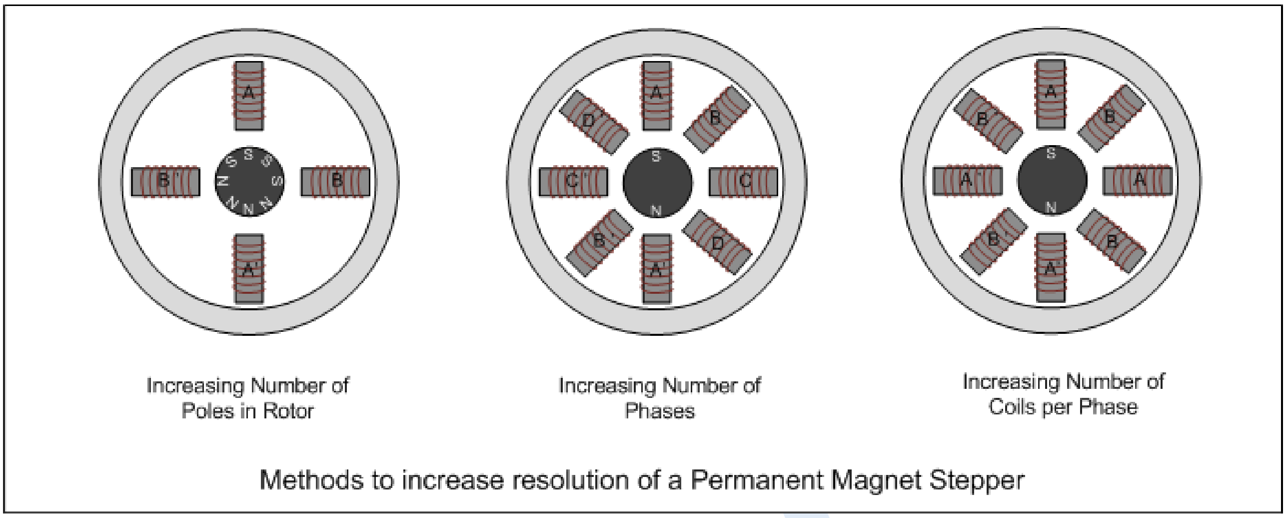


Fig. 5: Figure Showing Ways To Increase Resolution Of Permanent Magnet Stepper Motor

2. Variable reluctance stepper :

The variable reluctance stepper has a toothed non-magnetic soft iron rotor. When the stator coil is energized the rotor moves to have a minimum gap between the stator and its teeth.

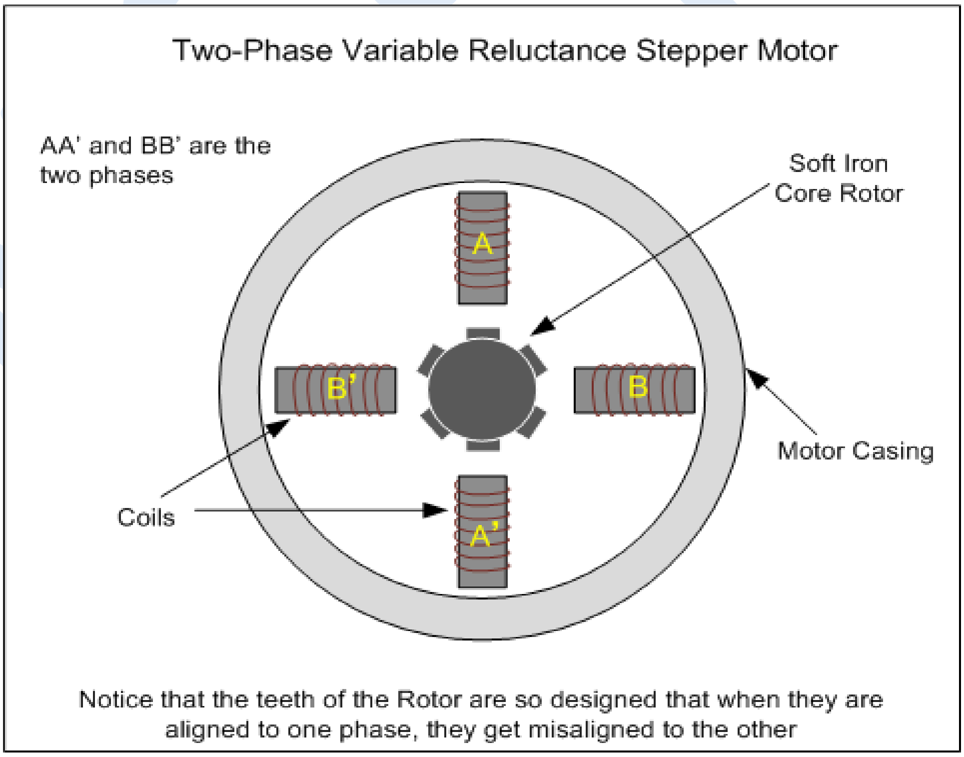


Fig. 6: Basic Diagram Of Two-Phase Variable Reluctance Stepper Motor

The teeth of the rotor are designed so that when they are aligned with one stator they get misaligned with the next stator. Now when the next stator is energized, the rotor moves to align its teeth with the next stator. This way energizing stators in a fixed sequence completes the rotation of the step motor.

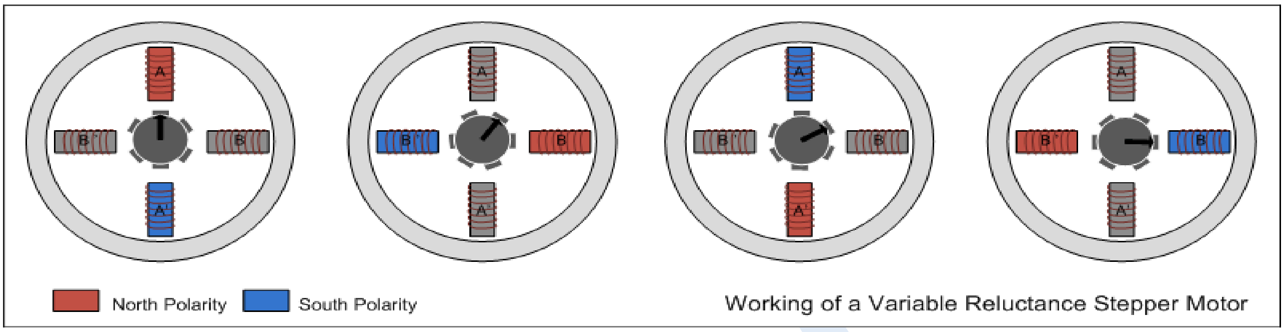


Fig. 7: Diagram Explaining Working Of Variable Reluctance Stepper

The resolution of a variable reluctance stepper can be increased by increasing the number of teeth in the rotor and by increasing the number of phases.

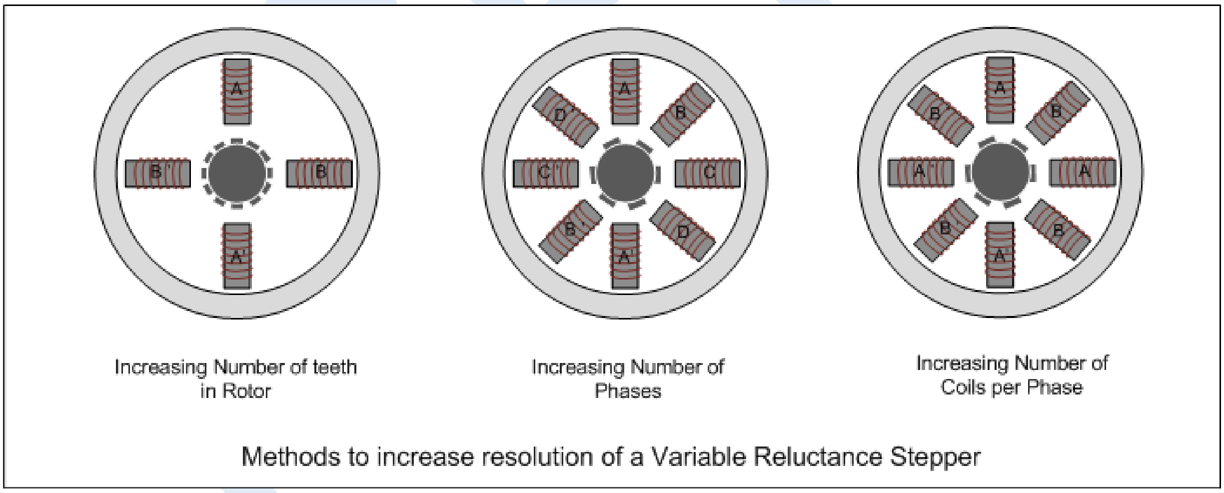


Fig. 8: Figure Showing Ways To Increase Resolution Of Variable Reluctance Stepper Motor

3. Hybrid stepper :

A hybrid stepper is a combination of both permanent magnet and the variable reluctance. It has a magnetic teethed rotor which better guides magnetic flux to preferred location in the air gap.

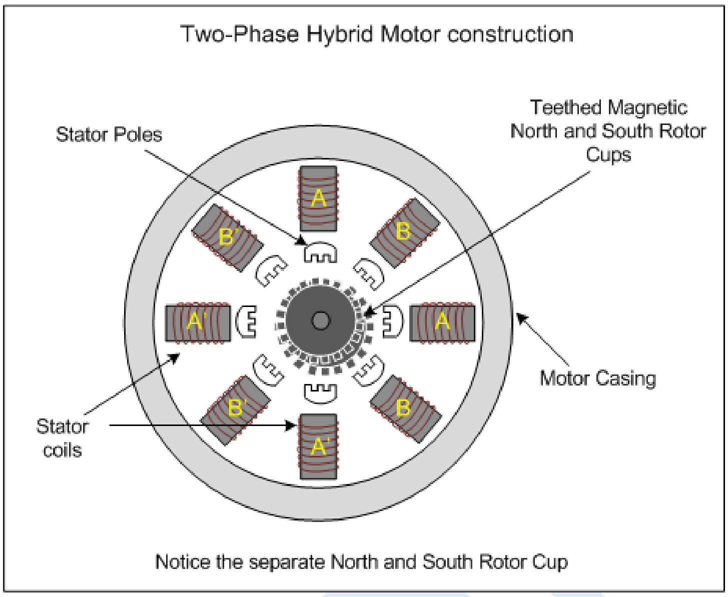


Fig. 9: Construction Of Two phase Hybrid Motor

The magnetic rotor has two cups. One for north poles and second for the south poles. The rotor cups are designed so that that the north and south poles arrange in alternative manner. Check out the insight of a Hybrid Stepper Motor.

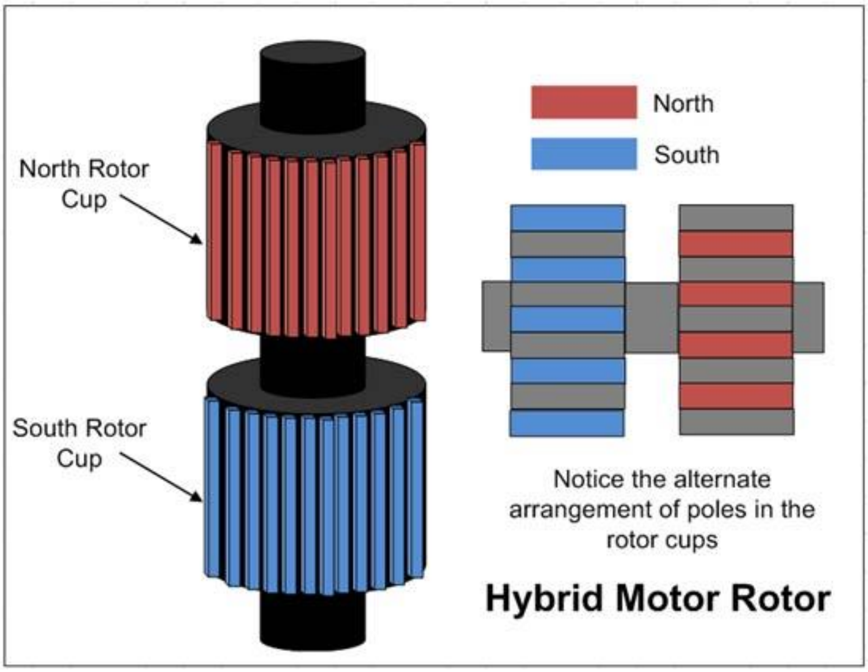


Fig. 10: Diagram Showing Internal Structure Of Magnetic Rotor In Hybrid Motor

The Hybrid motor rotates on same principle of energizing the stator coils in a sequence.

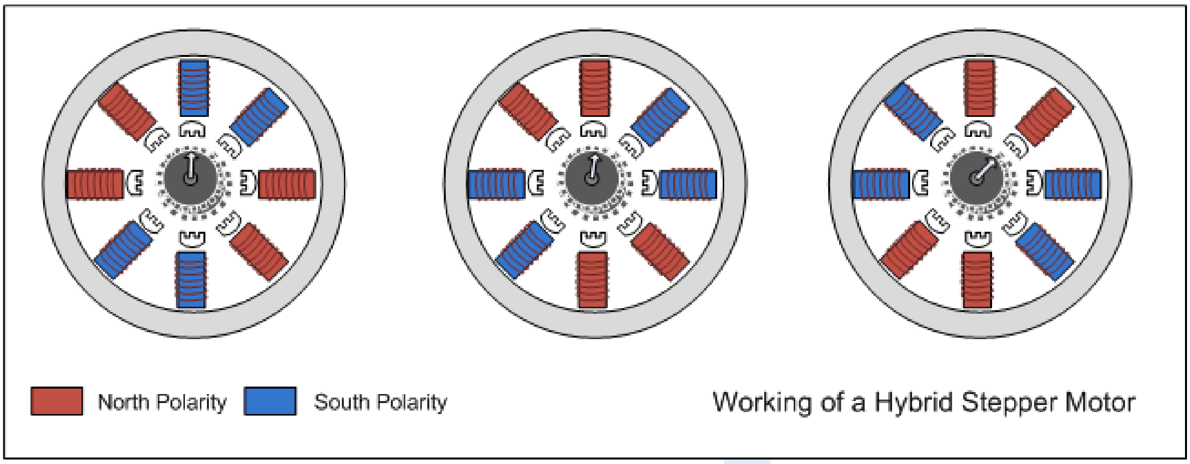


Fig. 11: Diagram Explaining Working Of Hybrid Stepper Motor

Stepping Modes

There are three stepping modes of a stepper motor. The stepping mode refers to the pattern of sequence in which stator coils are energized.

1. Wave drive (One phase ON at a time)
2. Full drive (Two phase ON at a time)
3. Half drive (One and two phase ON at a time)

1. Wave drive :

In wave drive stepping mode only one phase is energized at a time.

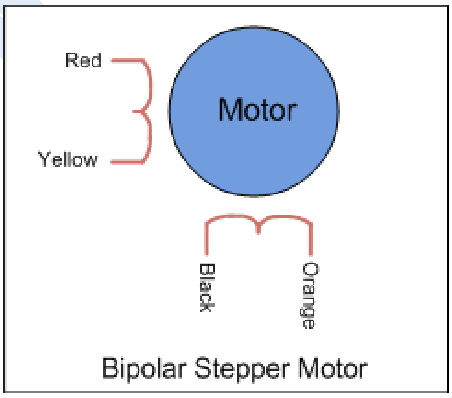


Fig. 14: Wave Drive Stepping Mode Pattern In Stepper Motor

2. Full Drive :

In full drive, two phases are energized at a time.

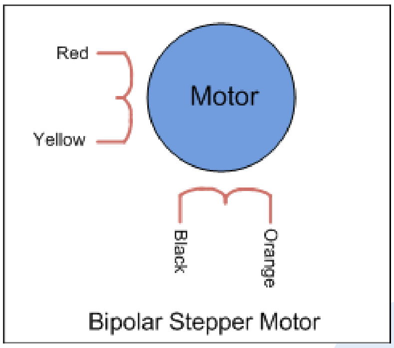


Fig. 15:Full Drive Stepping Mode pattern In Stepper Motor

3. Half Drive :

In half drive, alternately one and two phases are energized. This increases the resolution of the motor.

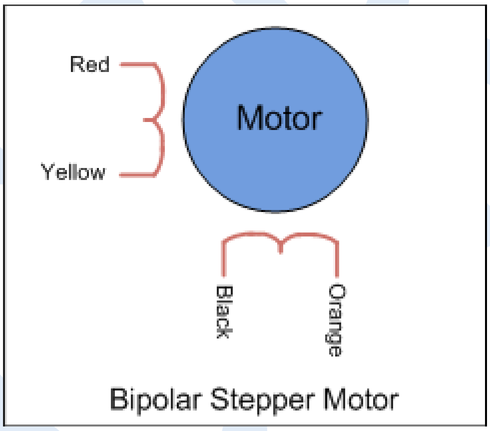


Fig. 16: Half Drive Stepping Mode Pattern In Stepper Motor

Advantages:

1. The rotation angle is proportional to the input pulses.
2. Full torque at standstill.
3. Very low-speed synchronous rotation is possible to achieve.
4. There are no brushes so it is reliable.
5. Speed is directly proportional to the frequency of the input as pulses; hence a wide range of rotational speed can be realized.
6. Low speed with high precision.

Disadvantages:

1. No feedback system.
2. Low effitiency.
3. May produce more noise.
4. Difficult to operate at very high speed.
5. For the smooth move, micro stepping is required.

Applications:

1. Factory automation.
2. Packaging.
3. Material handling.
4. Aerospace industry especially in avionics.
5. 3D pictures acquisition system.
6. Laser measurements.
7. Robotics.

SERVO MOTORS/ SERVO MECHANISMS

A servo motor is a basic electrical device that is used to rotate or move the gadgets with great precision and accuracy at different angles and with different velocities. It is a closed-loop feedback-controlled system. The main feature that distinguishes it from other motors is its propensity to work accurately with distance and precise angles. It can rotate the object in both counterclockwise as well as in a clockwise direction with the same capability. Servo motors are usually rated in kg/cm while other motors are usually rated in KVA. It means how much weight does a motor can lift if the load is suspended at a specific distance from the shaft of motor.it is of great importance in industrial application where accurate movements are required.

There are practically two types of servo motor depending how it is powered

- **AC servo Motor**

- **DC servo motor**

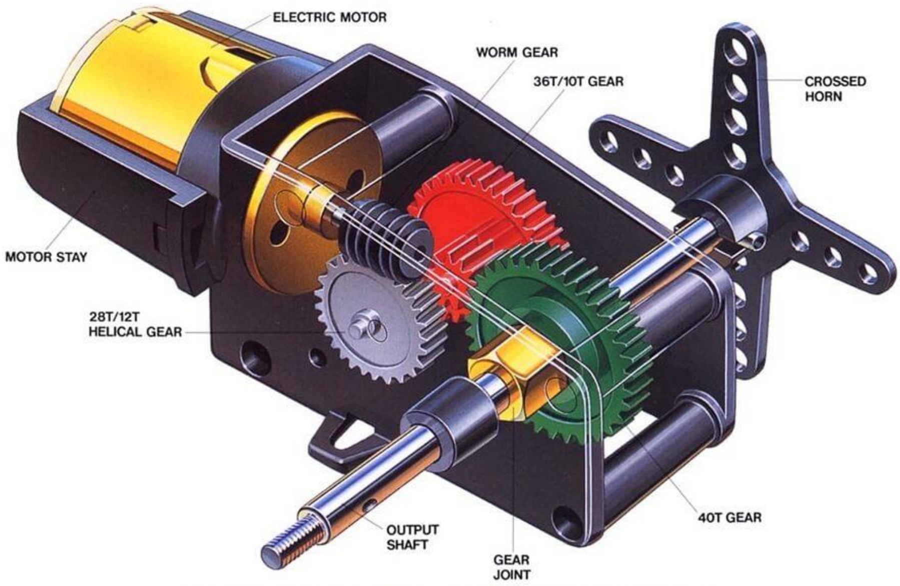
AC servo motor is powered with an AC source while DC servo motor is powered with a DC source. AC servo motor has less efficiency, operates smoothly, delivers low power, small weight, and low maintenance is required. Whereas, DC servo motor has high efficiency, delivers high power, large weight, and requires time to time maintenance. AC motor finds its applications in high speed working**.**

Construction

Servo motor is conventionally constructed by using the ordinary motor, position sensors, gear system and a controlled circuit. The controller can be any microcontroller like Arduino, STM, TIVA, etc. While position sensor can be Encoder for AC servo motors used in Industries and it is a potentiometer for DC servo motors.

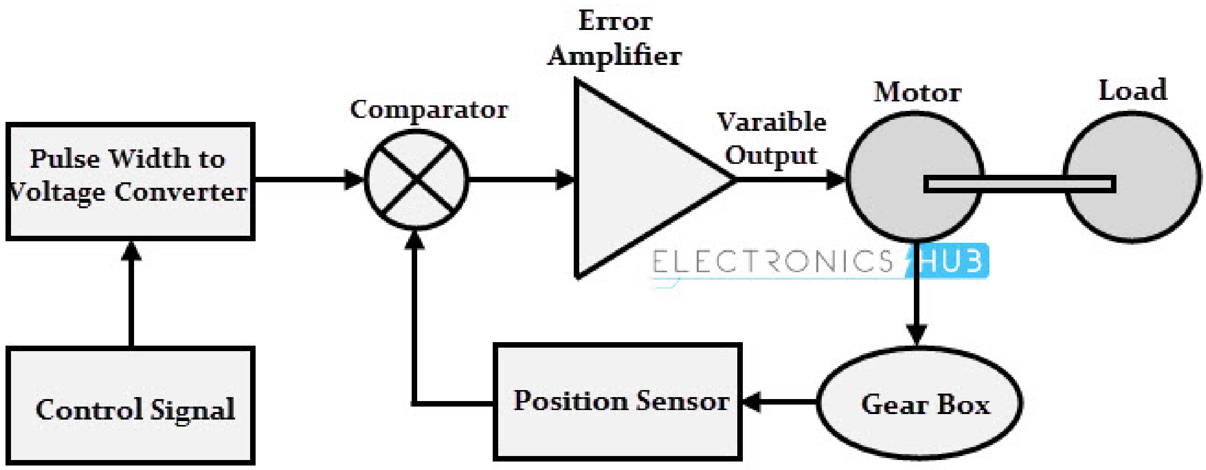
The Servo motor is DC motor or AC Motors which has 5 following parts:-

1. **Stator Winding:** This type of winding wound on the stationary part of the motor. It is also known as field winding of the motor.
2. **Rotor Winding:** This type of winding wound on the rotating part of the motor. It is also known as an armature winding of the motor.
3. **Bearing:** These are of two types,i.e, font bearing and back bearing which are used for the movement of the shaft.
4. **Shaft:** The armature winding is coupled on the iron rod is known as the shaft of the motor.
5. **Encoder:** It has the approximate sensor which determines the rotational speed of motor and revolution per minute of the motor.



Construction of Servo Motor

A DC servo motor is constructed by using DC motor which has armature and field winding coupled with gearbox, controller and Potentiometer, while AC servo motor is constructed using an Induction motor consisting of rotor and stator with gear system and Encoders.



Mechanism of Servo Motor

It consists of three basic types:

1. Controlling Device
2. Output Sensor
3. Feedback system

The servo motor works on the phenomenon of the automatic closed-loop system. The controller is required for this closed-loop system. This controller is composed of a comparator and a feedback path. It has one output and two inputs. In this, for producing an output signal, the comparator is used to compare the required reference signal and this output signal is sensed by the sensor. The input signal for the motor is termed as a feedback signal. On the basis of the feedback signal, the motor starts working. Comparator signal is called a logic signal of the motor. The motor would be ON for the desired time when the logical difference is higher and the motor would be OFF for the desired time when the logical difference is lower. Basically, a comparator is used to decide that motor would be ON or OFF. Proper functioning of the motor can be done with the help of a good controller.

Working

Servo motor is basically a closed loop feedback system. A closed loop feedback system controls the output of the system by varying input. The output is compared with a reference signal and error is generated; this error signal is the input signal to controller which generates a PWM according to the error. PWM is the input of the motor, the output of the motor is sensed by position sensor and this is compared with input and again error signal is generated This process continues until the error signal is zero, means there is no difference between output and referenced signal. The amount of rotation is determined by the duty cycle of the pulse. The figure below shows that if ON time of the pulse is less than a specific time period, it rotates below 90 degree and if it is greater, than it rotates till 180 degrees.

In DC servo motors the input signal is applied to dc motors which in turns rotates the shaft and gears, the rotation of gears is basically our output which is fed back to potentiometer whose knobs rotates and changes its resistance. As resistance is changed so voltage is varied which is error signal that is fed into controller and accordingly PWM is generated.

The DC motor has armature and field winding, one of the winding is provided with fixed voltage while the other winding is powered with varying error signal. Let's assume we are using armature-controlled method in which torque depends upon the armature current which means error signal is provided to armature which controls the torque of the motor.

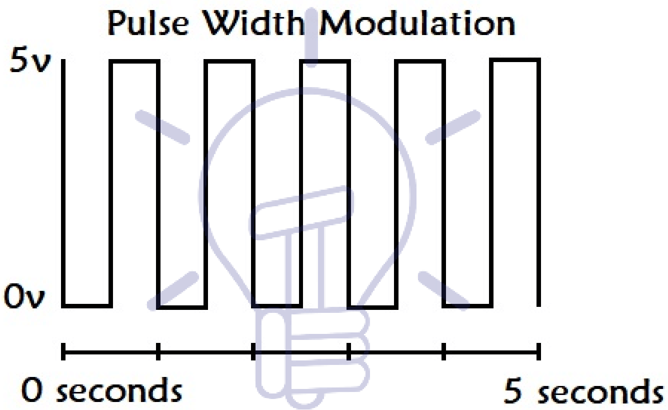
In AC servomotors we have two parts rotor and stator. A stator has two windings reference winding and controlled winding which are displaced by 90 degrees. Fixed signal is applied at reference winding while a variable error signal is applied at the controlled winding.

As error signal is applied to the stator both the windings produce a flux which is at a phase difference with each other, so torque is produced, and rotor starts rotating. After that the output is fed back to encoder which sense the speed and accordingly send signal to microcontroller.

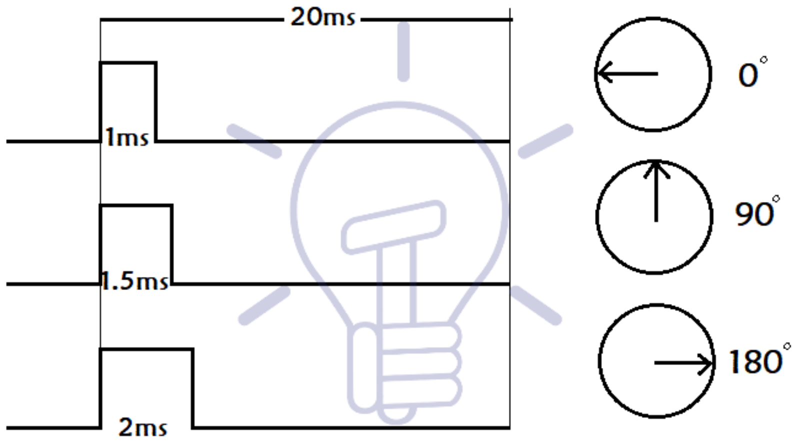
Controlling of Servo Motor:

The servo motors can be controlled by the method PWM i.e., Pulse Width Modulation. These send electric signals of inconsistent width to the motor. The width pulse is varied in the range of 1 millisecond to 2 milliseconds and transfer this to the servo motors with repeating 50 times in a second. The width of the pulse controls the angular position of the rotating shaft. In this, three terms are used which shows the controlling of the servomotor i.e., a maximum pulse, minimum pulse and repetition rate.

For example, The servo moves with the pulse of 1 millisecond to turn motor towards 0˚ whereas a pulse of 2 milliseconds to turn motor towards 180˚ Between the angular positions, the pulse width interchange by itself. Therefore, the servo turns to the 90˚ with the pulse of width 1.5 milliseconds.



There are three wires or leads in every servo motors. The two wires used from positive supply and ground supply whereas the third wire is used to control the signal.



Applications of Servo Motors

Here are some applications used to control speed when the servo is over headed or over rotating:

- They are used to control the positioning and movement of elevators in radio controlled airplanes
- They play an important role in robotics information of robot because of their smooth switching on or off and accurate positioning.
- They are used in hydraulic systems to maintain hydraulic fluid in the aerospace industry.

- In radio controlled toys these are also used.
- They are used to extend or replay the disc trays in electronic devices such as DVDs or Blue-ray Disc players.
- They are used to maintain the speed of vehicles in the automobile industries.

Advantages & Disadvantages of Servo Motors

Advantages:

- The driver will increase the current to the motor coil when we place a heavy load on the motor as it attempts to rotate the motor.
- In servo motor, the High-speed operation will be possible.

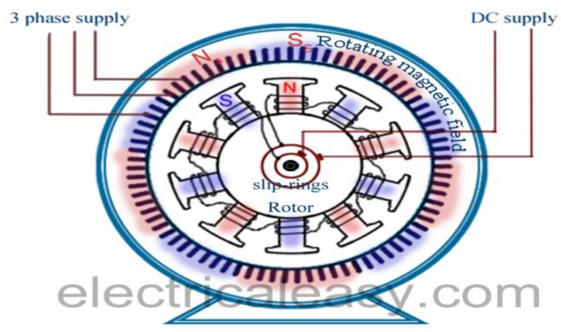
Disadvantages:

- The cost will be higher.
- The servo motor is not suitable for precision control of rotation because the servo motor is trying to rotate according to the command pulses, but lags behind.

SYNCHRONOUS MOTORS

Synchronous motor and induction motor are the most widely used types of AC motor. Construction of a synchronous motor is similar to an alternator (AC generator). A same **synchronous machine** can be used as a synchronous motor or as an alternator. Synchronous motors are available in a wide range, generally rated between 150kW to 15MW with speeds ranging from 150 to 1800 rpm.

Construction Of Synchronous Motor

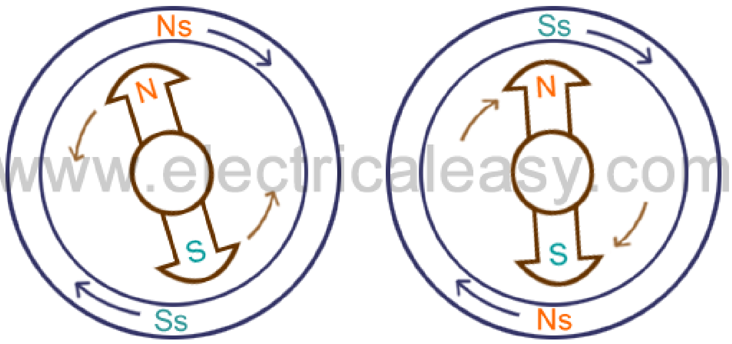


The **construction of a synchronous motor** (with salient pole rotor) is as shown in the figure at left. Just like any other motor, it consists of a stator and a rotor. The stator core is constructed with thin silicon lamination and insulated by a surface coating, to minimize the eddy current and hysteresis losses. The stator has axial slots inside, in which three phase stator winding is placed. The stator is wound with a three phase winding for a specific number of poles equal to the rotor poles.

The **rotor in synchronous motors** is mostly of salient pole type. DC supply is given to the rotor winding via slip-rings. The direct current excites the rotor winding and creates electromagnetic poles. In some cases permanent magnets can also be used. The figure above illustrates the **construction of a synchronous motor** very briefly.

Working Of Synchronous Motor

The stator is wound for the similar number of poles as that of rotor, and fed with three phase AC supply. The 3 phase AC supply produces rotating magnetic field in stator. The rotor winding is fed with DC supply which magnetizes the rotor. Consider a two pole **synchronous machine** as shown in figure below.



- Now, the stator poles are revolving with synchronous speed (lets say clockwise). If the rotor position is such that, N pole of the rotor is near the N pole of the stator (as shown in first schematic of above figure), then the poles of the stator and rotor will repel each other, and the *torque produced will be anticlockwise*.
- The stator poles are rotating with synchronous speed, and they rotate around very fast and interchange their position. But at this very soon, rotor can not rotate with the same angle (due to inertia), and the next position will be likely the second schematic in above figure. In this case, poles of the stator will attract the poles of rotor, and *the torque produced will be clockwise*.
- Hence, the rotor will undergo to a rapidly reversing torque, and the motor will not start.

But, if the rotor is rotated upto the synchronous speed of the stator by means of an external force (in the direction of revolving field of the stator), and the rotor field is excited near the synchronous speed, the poles of stator will keep attracting the opposite poles of the rotor (as the rotor is also, now, rotating with it and the position of the poles will be similar throughout the cycle). Now, the rotor will undergo unidirectional torque. The opposite poles of the stator and rotor will get locked with each other, and the rotor will rotate at the synchronous speed.

Characteristic Features Of A Synchronous Motor

- Synchronous motor will run either at synchronous speed or will not run at all.

- The only way to change its speed is to change its supply frequency. (As Ns = 120f / P)
- Synchronous motors are not self starting. They need some external force to bring them near to the synchronous speed.
- They can operate under any power factor, lagging as well as leading. Hence, synchronous motors can be used for power factor improvement.

Application Of Synchronous Motor

- As synchronous motor is capable of operating under either leading and lagging power factor, it can be used for power factor improvement. A synchronous motor under no-load with leading power factor is connected in power system where static capacitors can not be used.
- It is used where high power at low speed is required. Such as rolling mills, chippers, mixers, pumps, pumps, compressor etc.

APPENDIX I

CONTENT BEYOND THE SYLLABUS

APPENDIX I

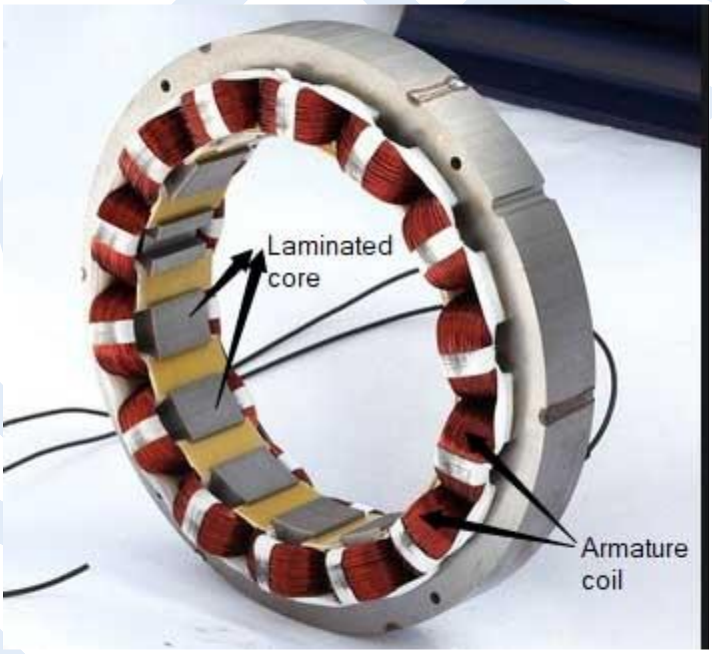
ALTERNATORS

CONSTRUCTION OF ALTERNATOR/ SYNCHRONOUS GENERATOR

- The AC generator (alternator) or synchronous generator is a machine which converts the mechanical power or energy into electrical power.
- The construction of an alternator is very similar to the DC generator but the main difference between them in DC generator the armature winding is the rotating part and field winding is the stationary part whereas in an alternator the armature winding is stationary and field winding is the rotary part.

Stator

- As the name suggests it is the stationary part of the machine and it is made up of special magnetic material which can allow high magnetic permeability and low magnetic hysteresis such as fabricated steel.



Alternator stator

- The stator core is laminated to minimize the effect of eddy current losses.The lamination is insulated from each other by a thin coating of an oxide and has space between them to allow passage of cool air flow.
- For the small machine, the laminations are stamped out in the complete ring structure and for the large machine, the laminations are divided into the number of segments.
- The slots are provided in the inner periphery of the core and the armature conductors or coils are assembled in it.

- Generally, open slots are used permitting easy installation or removal of the stator coil.
- The fractional number of slots per pole is used in order to eliminate the harmonic in the waveform.
- The armature winding of an alternator is usually connected in star and its neutral is connected to the ground.

Why is the Armature winding of an Alternator connected in Star?

- The phase voltages in star connection are 57.7 % of the line voltages, i.e. the armature winding in star connection is less exposed to voltage as compared to the delta connection which in turn prove more economic if we consider insulation, breakdown strength, the requirement of conductor material etc.
- In star connection, if the neutral is grounded then it also provides a path for the Zero-Sequence currents during faults, whereas in the delta connection the zero sequence currents flow within the delta circuit and hence increasing the load on the winding.

Rotor

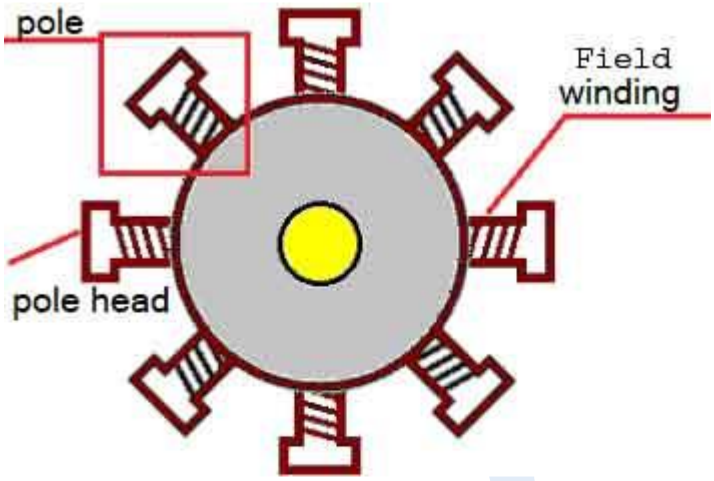
- The revolving field structure of the electrical machine is called as the rotor. In a synchronous generator, the rotor carries a field winding which is supplied by the DC source.
- The DC source is also called an exciter which is generally a small d.c shunt or compounded generator mounted on the shaft of the alternator.

There are two types of rotor construction

- Salient Pole Type
- Cylindrical Type (non-salient pole)

Salient (or projecting Pole) Type

- The salient pole type rotor is used for low and medium speed machines (less than 1200 rpm) and have the large diameter and small axial length.



Salient Pole Rotor

- The poles are made up of thick steel lamination to reduce eddy current heating loss and it is attached to a rotor by means of the dovetail joint.
- In salient pole rotor, the poles are always projected in the outward direction as shown in the figure.
- The field winding in the salient pole type is connected in series in such a way that when the field winding is energised by the exciter, then adjacent poles will have opposite polarities. The number of poles does not affect the number of phases in the alternator output.
- To reduce the effect of haunting damper winding is provided in the pole faces. They don't let the motor to oscillate abruptly, they damp the oscillations thus increasing the stability of the machine.
- Salient pole rotor found application for diesel engine and water turbine because they both required medium speed (120-1000 rpm).
- The pole and Pole shoe cover 2/3 of the pole pitch.
- The rating of salient pole rotor is less than 500 kW.

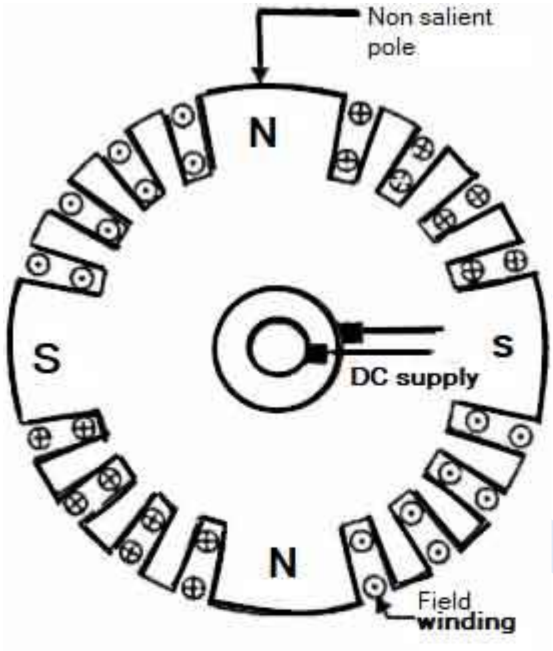
Disadvantage of Salient Pole Rotor

The salient pole rotor has following disadvantages

- The salient pole rotor cause excessive windage looses if they are driven at high speed and it also increases the noise produced by an alternator.
- The construction of salient pole rotor cannot withstand high mechanical stress.
- The speed of an alternator is inversely proportional to the numbers of pole required ($N_s = 120f/p$) so to operate a salient pole type alternator, a large number of poles are required which increases the diameter of the generator thus increasing space requirement for installation and initial cost due to extra material used.

Smooth Cylindrical Type | Non-Salient Pole Alternator

- This type of Rotor is used for steam driven alternator i.e turbo alternator which runs at very high speed.



Cylindrical Type Rotor

- The Rotor is made up of smooth solid forgings of alloy steel cylinder having the number of slots along the outer periphery.
- The field windings of cylindrical type rotor are connected in series to the slip rings through which they are excited by the DC exciter.
- The top portion of the slot is covered with the help of steel or manganese wedges and the unslotted portion of the cylinder acts as the poles of an alternator.
- The field windings are arranged in such a way that its flux density is maximum on the polar central line.
- In cylindrical rotor, the pole doesn't project out from the smooth surface of the rotor hence they maintain the uniform air gap between stator and rotor.
- Since steam turbine runs at very high speed, therefore, they required less number of poles hence the diameter of the rotor is small and axial or rotor length is large.

Advantages of Cylindrical Rotor type Alternator

- The main advantages of the cylindrical rotor are that their construction has mechanical robustness and gives noiseless operation at very high speed (1500-3000 rpm).
- The flux distribution is nearly uniform sine wave hence better waveform is obtained.

- The hunting effect is very rare in the cylindrical rotor, therefore, there is no need to provide damper winding except in case of assisting the alternator for synchronising purpose.

Types Of Alternator

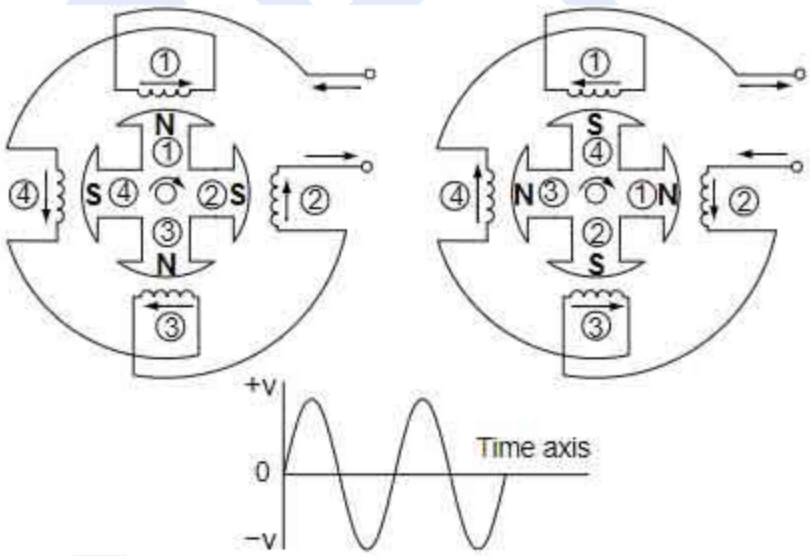
The alternator can be divided into different types based on their application, prime mover, design, output power, and cooling.

Alternator Based on their Output Power

- Single Phase Alternator
- Two-Phase Alternator
- Three Phase Alternator

SINGLE PHASE ALTERNATOR

The single phase alternator produces a continuous single alternating voltage. The armature coils are connected in series forming a Single circuit in which output voltage is generated.

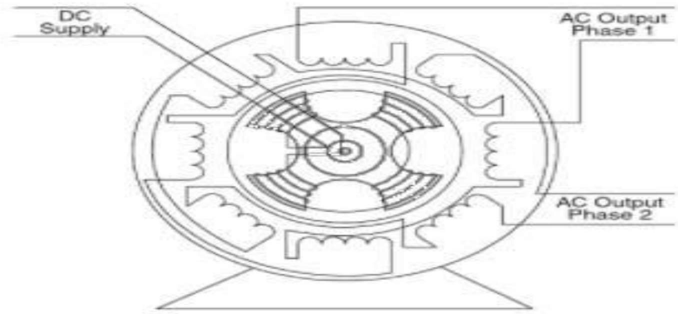


Single phase Alternator

In the above figure, the stator has four poles which are evenly spaced around the stator frame. The rotor also consists 4 poles and each pole has opposite polarity to its neighbours which are angled at 90 degrees. Each coil also has opposite winding to its neighbours. This configuration allows the lines of force at 4 poles to be cut by 4 coils at the same amount at a given time. At each 90-degree rotation, the voltage output polarity is switched from one direction to the other. Therefore, there are 4 cycles of the AC output in one rotation.

Single-phase generators are used as standby generators in case of the main power supply is interrupted and for supplying temporary power on construction sites.

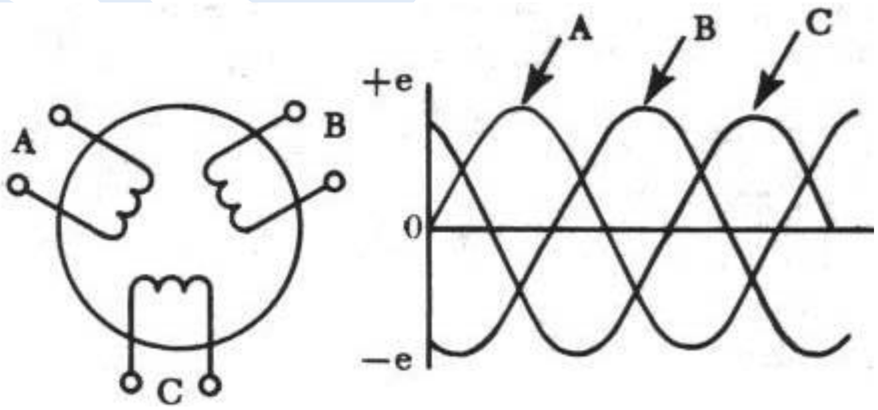
TWO-PHASE ALTERNATOR



Two-Phase Alternator

In a two-phase alternator, there are two single-phase windings spaced physically so that the ac voltage induced in one is 90° out of phase with the voltage induced in the other. The windings are electrically separate from each other. Suppose in the first quarter first winding produce maximum flux, then the second winding generates zero flux and in the second quarter the second winding generates maximum flux and first winding generate zero flux. This condition establishes a 90° relation between the two phases.

THREE PHASE ALTERNATOR



Three-phase-alternator

A three-phase alternator has 3 sets of single-phase windings arrangement so that the voltage induced in each winding is 120° out of phase with the voltages in the other two windings. These windings are connected in the star to provide a three-phase output.

Advantages of Three-phase Alternator

- The three-phase alternator gives the most constant output than the single phase alternator.
- Three phase power supply is more economical than the other two phases because three separate single-phase voltage can be delivered at the same time from the power system.

Alternator based on their applications

According to their application usage, the alternator can be divided into 5 main part.

- Automotive Type Alternator
- Diseal electric locomotive Alternator
- Brushless type Alternator
- Marine Type Alternator
- Radio Alternator

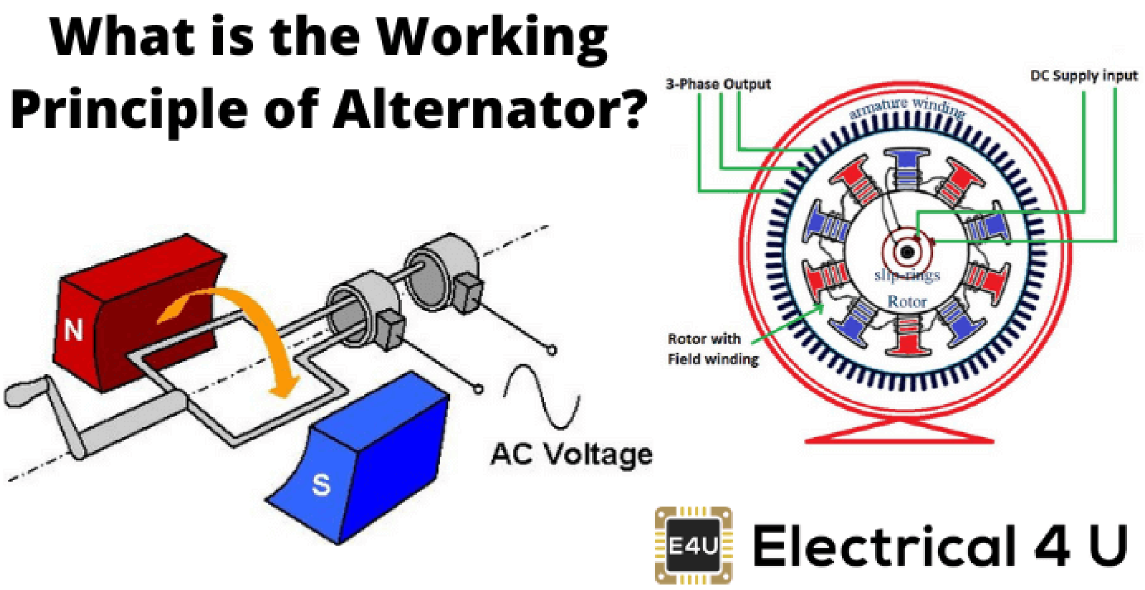
Alternator based on their Prime-mover

- Turbo Generator
- Hydro Generator
- Diseal Engine driven Alternator

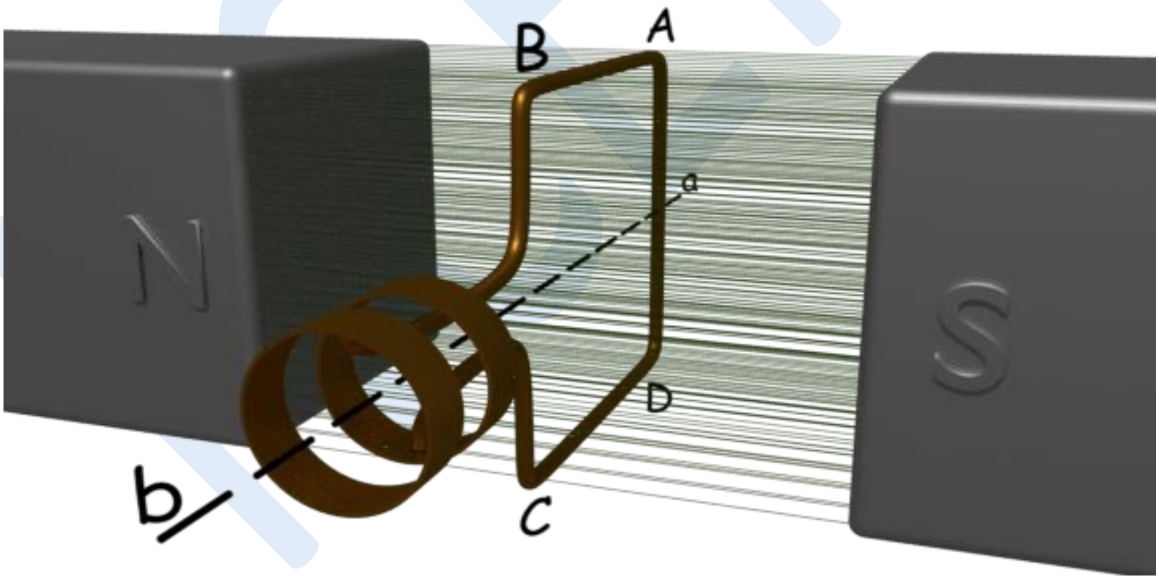
Alternator Based on Type of their Design

- Salient pole Rotor
- Smooth cylindrical Rotor

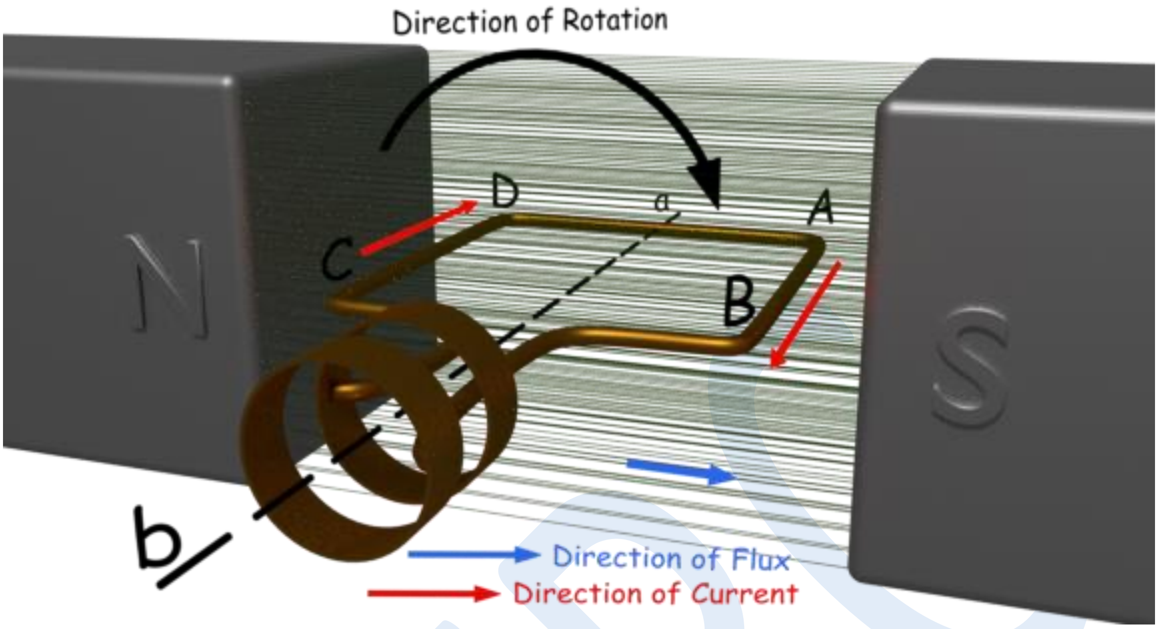
WORKING PRINCIPLE OF ALTERNATORS



The **working principle of an alternator** is very simple. It is just like the basic principle of DC generator. It also depends upon Faraday's law of electromagnetic induction which says the current is induced in the conductor inside a magnetic field when there is a relative motion between that conductor and the magnetic field.



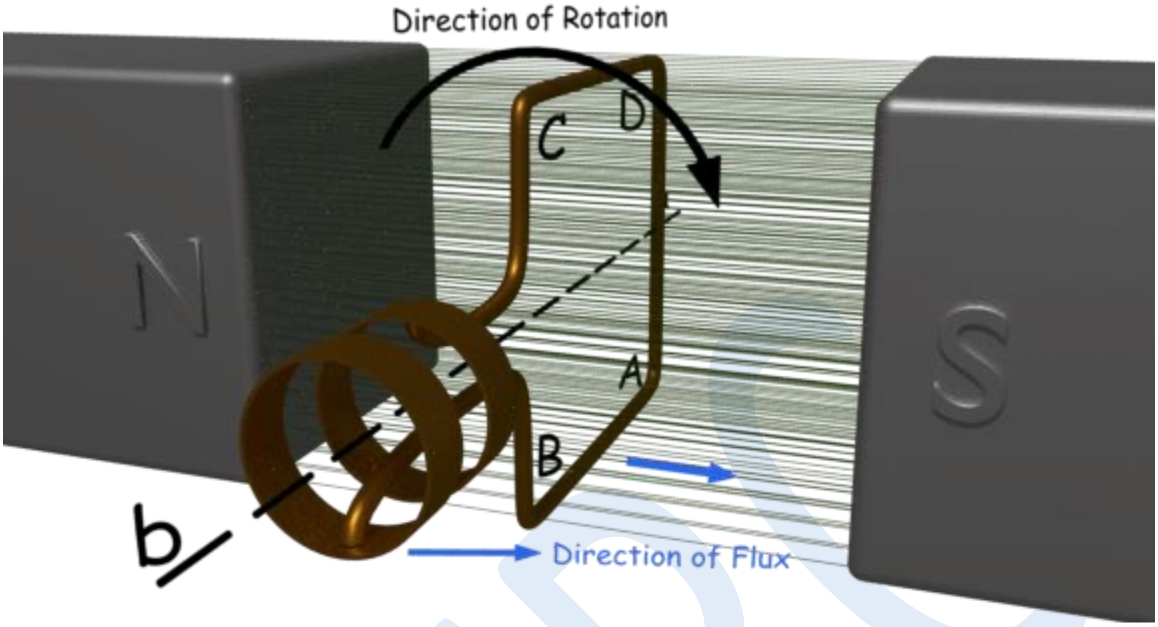
For understanding **working of alternator** let us think about a single rectangular turn placed in between two opposite magnetic poles as shown above.



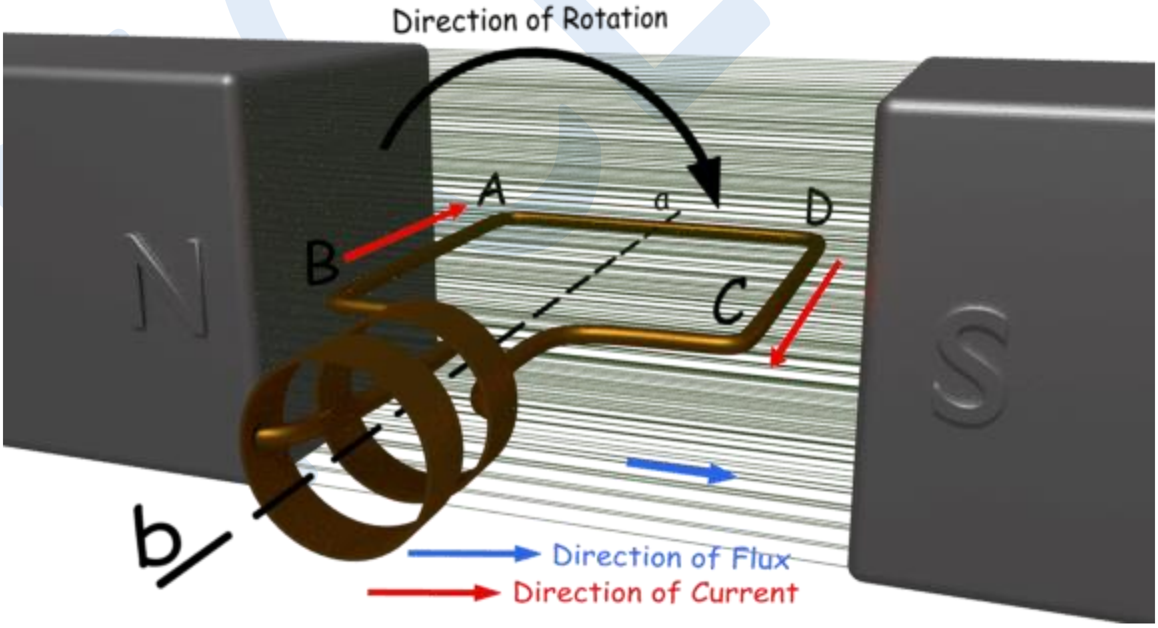
Say this single turn loop ABCD can rotate against axis a-b. Suppose this loop starts rotating clockwise. After 90^o rotation the side AB or conductor AB of the loop comes in front of S-pole and conductor CD comes in front of N-pole. At this position the tangential motion of the conductor AB is just perpendicular to the magnetic flux lines from N to S pole. Hence, the rate of flux cutting by the conductor AB is maximum here and for that flux cutting there will be an induced current in the conductor AB and the direction of the induced current can be determined by Fleming's right-hand rule. As per this rule the direction of this current will be from A to B. At the same time conductor CD comes under N pole and here also if we apply Fleming right-hand rule we will get the direction of induced current and it will be from C to D.

Now after clockwise rotation of another 90^o the turn ABCD comes at the vertical position as shown below. At this position tangential motion of conductor AB and CD is just parallel to the magnetic flux lines, hence there will be no flux cutting that is no current in the conductor.

While the turn ABCD comes from a horizontal position to a vertical position, the angle between flux lines and direction of motion of conductor, reduces from 90^o to 0^o and consequently the induced current in the turn is reduced to zero from its maximum value.



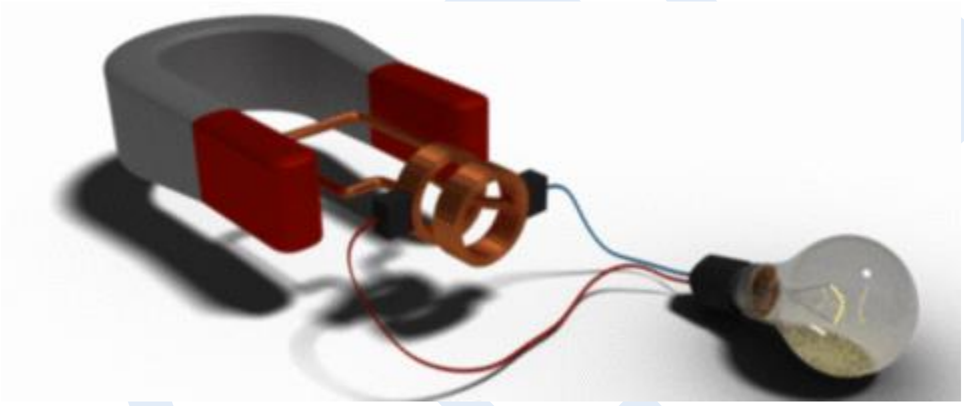
After another clockwise rotation of 90° the turn again comes to horizontal position, and here conductor AB comes under N-pole and CD comes under S-pole, and here if we again apply Fleming right-hand rule, we will see that induced current in conductor AB, is from point B to A and induced current in the conductor CD is from D to C.



As at this position the turn comes at a horizontal position from its vertical position, the current in the conductors comes to its maximum value from zero. That means current is circulating in the close turn from point B to A, from A to D, from D to C and from C to B, provided the loop is closed although it is not shown here. That means the current is in reverse of that of the previous horizontal position when the current was circulating as A → B → C → D → A.

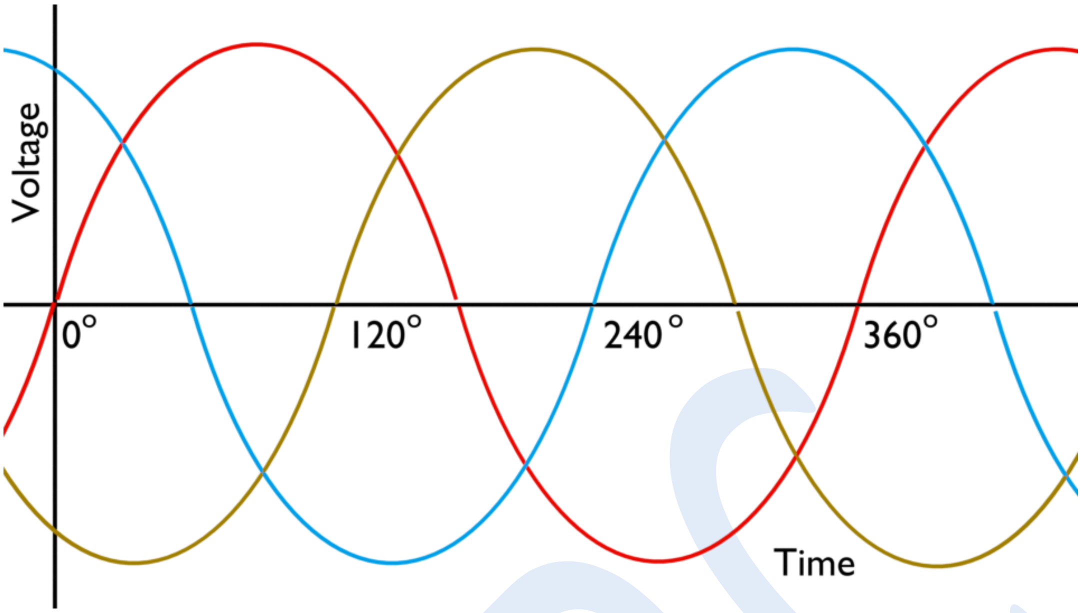
While the turn further proceeds to its vertical position the current is again reduced to zero. So if the turn continues to rotate the current in turn continually alternate its direction. During every full revolution of the turn, the current in turn gradually reaches to its maximum value then reduces to zero and then again it comes to its maximum value but in opposite direction and again it comes to zero. In this way, the current completes one full sine wave cycle during each 360^o revolution of the turn. So, we have seen how alternating current is produced in a turn is rotated inside a magnetic field. From this, we will now come to the actual **working principle of an alternator**.

Now we place one stationary brush on each slip ring. If we connect two terminals of an external load with these two brushes, we will get an alternating current in the load. This is our elementary model of an alternator.



Having understood the very basic principle of an alternator, let us now have an insight into its basic operational principle of a practical alternator. During the discussion of the basic working principle of an alternator, we have considered that the magnetic field is stationary and conductors (armature) is rotating. But generally in practical construction of alternator, armature conductors are stationary and field magnets rotate between them. The rotor of an alternator or a synchronous generator is mechanically coupled to the shaft or the turbine blades, which is made to rotate at synchronous speed N_s under some mechanical force results in magnetic flux cutting of the stationary armature conductors housed on the stator.

As a direct consequence of this flux cutting an induced emf and current starts to flow through the armature conductors which first flow in one direction for the first half cycle and then in the other direction for the second half cycle for each winding with a definite time lag of 120^o due to the space displaced arrangement of 120^o between them as shown in the figure below. This particular phenomenon results in three-phase power flow out of the alternator which is then transmitted to the distribution stations for domestic and industrial uses.



EMF EQUATION OF ALTERNATORS

The emf induced by the alternator or synchronous generator is three phase alternating in nature. Let us derive the mathematical equation of emf induced in alternator.

Let,

Z = number of conductors in series per phase.

Z = 2T, where T is the number of coils or turns per phase. One turn has two coil sides or conductor as shown in the below diagram.

P = Number of poles.

f = frequency of induced emf in Hertz

Φ = flux per pole in webers.

K_p = pitch factor, K_d = distribution factor,

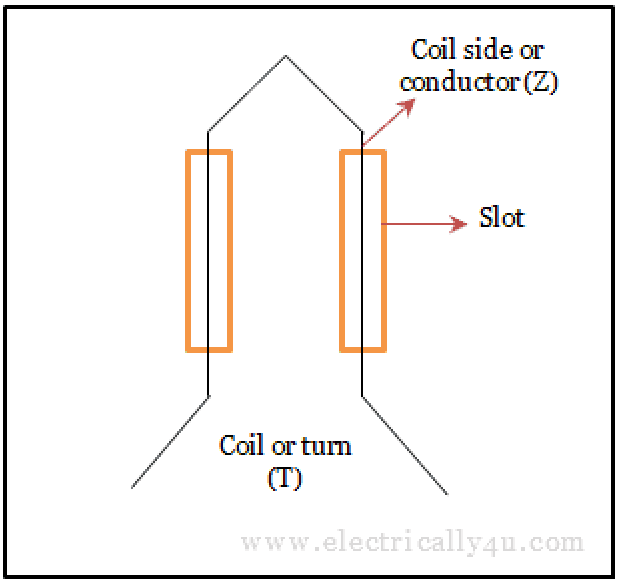
K_f = Form factor

N = Speed of the rotor in rpm(revolutions per minute)

N/60 = Speed of the rotor in revolutions per second.

Time taken by the rotor to complete one revolution,

dt = 1/(N/60)= 60/N second



Single turn coil

In one revolution of the rotor, the total flux Φ cut the by each conductor in the stator poles, dΦ = ΦP weber

By faraday's law of electromagnetic induction, the emf induced is proportional to rate of change of flux.

$$Average\ emf\ induced\ per\ conductor = \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi NP}{60}$$

We know, the frequency of induced emf

$$f = \frac{PN}{120},\ N = \frac{120f}{P}$$

Submitting the value of N in the induced emf equation, We get

$$Average\ emf\ induced\ per\ conductor = \frac{\Phi P}{60} x \frac{120f}{P} = 2\Phi f\ volts$$

If there are Z conductors in series per phase,

$$Average\ emf\ induced\ per\ conductor = 2\Phi fZ = 4\Phi fT\ volts$$

RMS value of emf per phase = Form factor x Average value of induced emf = 1.11 x 4 Φ f T

RMS value of emf per phase = 4.44 Φ f T volts

The obtained above equation is the actual value of the induced emf for full pitched coil or concentrated coil. However, the voltage equation gets modified because of the winding factors.

Actual induced emf per phase = 4.44 K_p K_d Φ f T volts = 4 K_f K_p K_d Φ f T volts

SAMPLE PROBLEM:

A 3 phase, 16 pole alternator has a star connected winding with 144 slots and 10 conductors per slot. The flux per pole is 0.02 Wb, sinusoidally distributed and the speed is 375 rpm. Find the frequency of the induced emf, phase emf and line emf. Assume the coil as full pitched.

Given parameters: P = 16, slots = 144 , Z = 10 conductors per slot, Φ = 0.02 wb, N = 375 rpm, for full pitch coil, $K_p = 1$.

To find : f, E_{ph}, E_L

Solution:

f= PN/120 = 16 x 375/120,

f = 50 Hz

The emf equation of alternator is given by, E_{ph}= 4.44 K_p K_d Φ f T volts

$$where,\ K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}}$$

Here, m = no. of slots/pole/phase = 144/16/3 = 3

where n=no. of slots/pole = 144/16 = 9

$\beta = 180^0/n = 180^0/9 = 20^0$

$$where,\ K_d = \frac{\sin \frac{3x20}{2}}{3 \sin \frac{20}{2}} = \frac{\sin 30}{3 \sin 10} = 0.96$$

Z = 10 conductors per slot per phase = 10 x 144/3 = 480

T = Z/2 = 480 /2 = 240

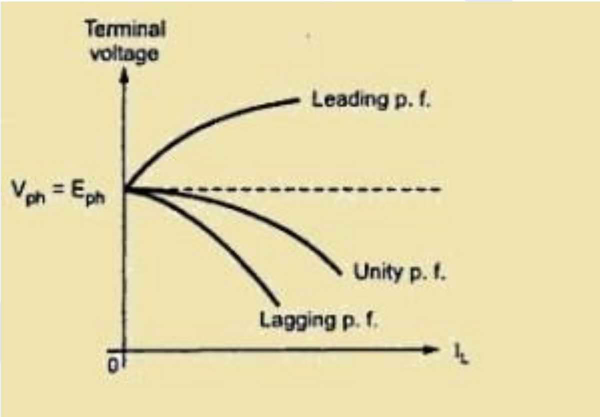
E_{ph}= 4.44 x 1 x 0.96 x 0.02 x 50 x 240 = 1022.97 V

$$E_L = \sqrt{3}\, E_{ph} = \sqrt{3}\ x\ 1022.97 = 1771.83\ V$$

VOLTAGE REGULATION OF ALTERNATORS

The voltage regulation of an alternator is defined as the change in its terminal voltage when full load is removed, keeping field excitation and speed constant, divided by the rated terminal voltage.

- The value of the regulation not only depends on the load current but also on the power factor of the load.
- For lagging and unity p.f. conditions there is always drop in the terminal voltage hence regulation values are always positive.
- While for leading capacitive load conditions, the terminal voltage increases as load current increases. Hence regulation is negative in such cases.
- The relationship between load current and the terminal voltage is called load characteristics of an alternator.



DETERMINATION OF VOLTAGE REGULATION

1. In the **case of small machines**, the regulation may be found by direct loading.

- The alternator is driven at synchronous speed and the terminal voltage is adjusted to its rated value *V*.
- The load is varied until the wattmeter and ammeter (connected for the purpose) indicate the rated values at desired p.f. Then the entire load is thrown off while the speed and field excitation are kept constant.
- The open-circuit or no-load voltage *E*0 is read.

$$\text{Percentage Voltage Regulation} = \left(\frac{|E_0| - |V|}{|V|}\right)$$

V = Rated terminal voltage

E0= No load induced e.m.f.

2. In the **case of large machines**, the cost of finding the regulation by direct loading becomes prohibitive.

- Hence, other indirect methods are used as discussed below.
- It will be found that all these methods differ chiefly in the way the no-load voltage *E*0 is found in each case.

1. The electromotive force (emf) method or synchronous impedance method
2. MMF method (or) ampere turn method
3. Zero power factor method
4. S.A (American standards association) method.

Let we see,

- **The electromotive force (emf) method or synchronous impedance method**: Even though this method gives the inconsistent result of voltage regulation it is quite useful because we consider drop due to armature reaction as drop due to synchronous reactance. It gives regulation more than actual value so it is called a pessimistic method.
- **MMF method (or) ampere turn method:** In MMF method, the reverse procedure is applied, i.e, each emf is replaced by an equivalent MMF. Here drop due to synchronous reactance is considered as drop due to armature reaction. It gives regulation less than actual value so it is called an optimistic method.
- **Zero power factor method:** It is also called a general method or Potier triangle method. Armature voltage and field currents are plotted and maintain the armature current at zero power factor lag called zero power factor characteristic.
- **S.A (American standards association) method:** This method is the combination of both MMF and zero power factor method.

DETERMINATION OF VOLTAGE REGULATION OF ALTERNATORS USING EMF METHOD

The voltage regulation of alternator by EMF method involves the EMF quantities of all the armature parameters (armature resistance, Armature leakage reactance, armature reaction). The drop due to armature reaction is not considered, because it does not occur due to any of the physical element but due to interaction of armature flux with main flux.

Hence, in order to quantify the voltage drop due to armature reaction, armature winding is assumed to have a fictitious reactance called armature reaction reactance X_{ar} Ω/phase.

Now, the Sum of armature leakage reactance and armature reaction reactance is called *synchronous reactance* of an alternator X_S.

$X_S = X_L + X_{ar}$

In EMF method, the voltage drop due to armature resistance (R_a) and the drop due to synchronous reactance(X_S) is considered, both the drops are emf quantities.

The impedance of armature winding is expressed as $Z_S = R_a + jX_S\ \Omega/phase$, which is nothing but the synchronous impedance of an alternator and since the drop due to the synchronous impedance is considered, this method is called ***synchronous impedance method***.

This method is also called ***pessimistic method***, because the voltage regulation obtained by this method is more than the actual value.

The EMF method requires the following data's to determine the voltage regulation of alternator.

- Armature resistance/phase
- Open circuit characteristics (OCC)
- Short circuit characteristics (SCC)

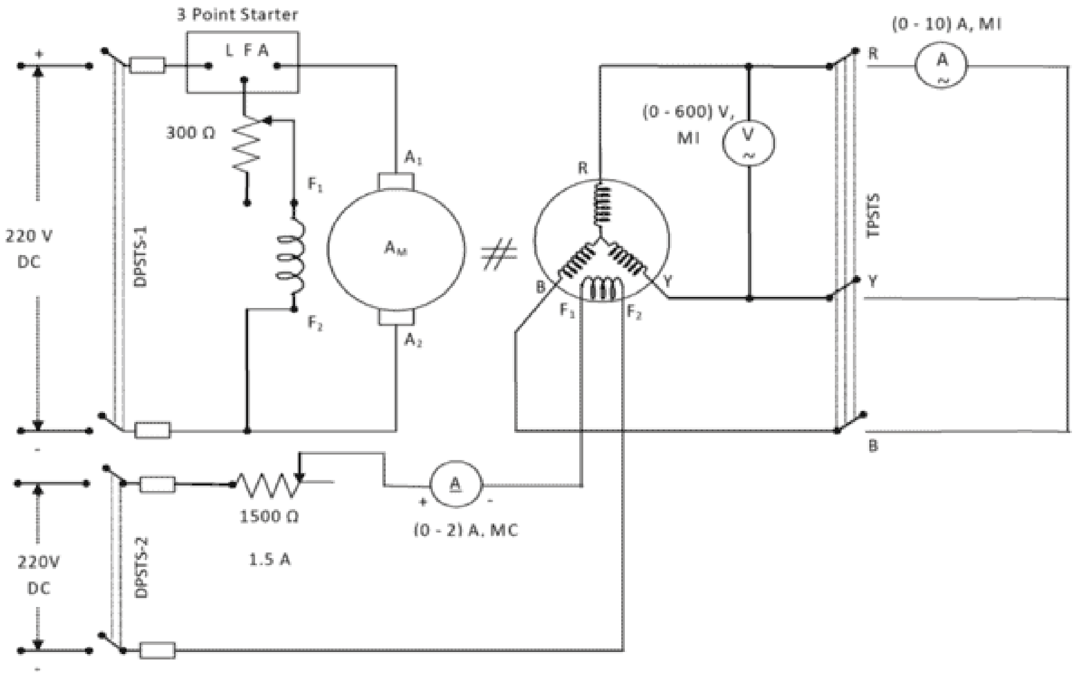
Armature Resistance per phase

Armature Resistance per phase can be obtained by conducting stator resistance test on the alternator. It is done by connecting the dc voltage supply to the stator armature winding and the corresponding current is measured.

By doing so, the dc stator resistance is calculated and then by using the formula $R_{ac} = 1.6\ R_{dc}$ the ac stator resistance is determined.

Open Circuit Characteristics(OCC)

- Open circuit characteristics is obtained by conducting open circuit test in the Alternator. To do that, the connections are given as per the following circuit diagram.
- To perform this test, the stator windings are kept open.
- The Alternator was made to run at synchronous speed by adjusting the field rheostat of the dc motor.
- The field current of the alternator was varied in steps until the machine attains its maximum voltage. The corresponding readings were noted down.
- From the readings, a graph is drawn as below, where OCC represents the open circuit characteristics.

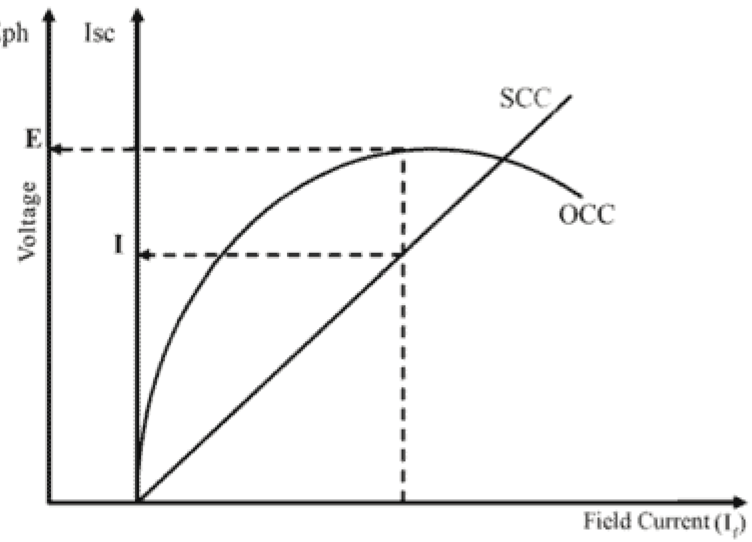


Experiment to determine the voltage regulation by EMF method

Short Circuit Characteristics(SCC)

- Short circuit characteristics is obtained by conducting short circuit test in the Alternator. To do that, the connections are given as per the above circuit diagram.
- The stator windings of alternator are Shorted and an ammeter is connected to measure the current flow.
- The Alternator was made to run at synchronous speed by adjusting the field rheostat of the dc motor.
- The field current of the Alternator was adjusted so that the armature current reaches its maximum rated value.
- Note the corresponding current readings and draw the graph. SCC in the graph below represents the short circuit characteristics.

Determination of Zs from the graph



Model Graph for determining the voltage regulation by EMF method

The value of Zs to be determined for the "**SAME VALUE OF FIELD EXCITATION**". Follow the simple procedure to draw the graph and obtain the voltage regulation.

1. Plot the OCC and SCC curve in a graph.
2. For the rated full load current(I_{sc}) of alternator[which is to be found from the rating of alternator], draw a line that cuts the SCC curve, from that draw a vertical line towards the x-axis and find the field current(I_f).
3. For that field current, extend the line so that it cuts the OCC curve and find the open circuit voltage V_{oc} volts (phase value).
4. Now, we know the open circuit voltage V_{oc} volts and short circuit current I_{sc}. From this, determine the value of Z_S using the formula,

$$Z_s = \frac{V_{oc}}{I_{sc}}$$

5. From the known resistance value and determined Z_S found the value of Xs using the formula,

$$X_s = \sqrt{Z_s^2 - R_a^2}$$

6. Now, using the following formulas, obtain the value for Eph, [obtained from phasor diagram]

For Lagging Power factor,

$$E_{ph} = \sqrt{(V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi + I_a X_s)^2}$$

For Leading Power factor,

$$E_{ph} = \sqrt{(V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi - I_a X_s)^2}$$

7. Finally the voltage regulation of alternator can be determined from the formula,

$$Voltage\ Regulation = \frac{E_{ph} - V_{ph}}{V_{ph}}$$