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

MRT 201 ELECTRICAL MACHINES AND DRIVES

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	To understand the construction and working of DC Machines
CO 2	Acquire basic knowledge in Transformers and Three Phase Induction Motors
CO 3	Enumerate the fundamentals knowledge in single phase Induction Motors and Alternators
CO 4	Familiarize the various special machines and power electronics devices.
CO 5	Understand the basic concepts of various electrical drives.

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

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

SYLLABUS

SYLLABUS

Module 1 – DC MACHINES

DC generator - constructional details and Working principle – EMF equation – types of dc generators – no load and load characteristics of dc generator. DC motor - Working principle - back emf – types of dc motor - equations for torque & power (simple numerical problems) - Necessity of starters and their types—power flow diagram.

Module 2 - TRANSFORMERS & 3-PHASE INDUCTION MOTORS

TRANSFORMERS

Working principle - Construction - core and shell type - emf equation – voltage transformation ratio (simple numerical problems) – concept of ideal transformer- phasor diagram -ideal, no-load, load – short circuit and open circuit test on transformer (basic concept only) - lossesin transformer

3-PHASE INDUCTION MOTORS

Constructional details – operation – concept of rotating magnetic field – slip - torque equation - (simple numerical problems) - torque–slip characteristics – starting methods of 3-pahse induction motors

Module 3 1-PHASE INDUCTION MOTORS &ALTERNATOR

1-PHASE INDUCTION MOTORS- Working principle – double revolving field theory – different types – split phase – capacitor start – capacitor start- run

ALTERNATOR - Constructional details – working principle - emf equation –voltage regulation – determination of voltage regulation – EMF method only (numerical problems).

Module 4 -- SPECIAL ELECTRICAL MACHINES & INTRODUCTION TO POWER ELECTRONICS

SPECIAL ELECTRICAL MACHINES

Universal motor – stepper motor -different types – servomotor (mechanism only) - Synchronous motor

INTRODUCTION TO POWER ELECTRONICS

Introduction – SCR -symbol, construction and modes of operation – V-I characteristics- Basic concepts of Rectifier – single phase half-wave controlled rectifier with R load – fully controlled bridge rectifier with R load – basic concept of inverter

Module 5 --ELECTRICAL DRIVES

Electrical Drives - Parts of electrical drives - Choice of electric drives - Status of DC and AC drives - Dynamics of Electric drives - Fundamental torque equations – Speed torque conventions and multi-quadrant operation - Components of load torque - Nature and classification of load torque – Steadystate stability – load equalization - Three phase Induction motor drives - Stator voltage control - Frequency control - Voltage and frequency control

QUESTION BANK

MODULE I				
Q:NO:	**QUESTIONS**	**CO**	**KL**	**PAGE NO:**
1	Derive EMF equation of DC Generator	CO1	K5	19
2	With neat sketch explain the construction of DC Machines	CO1	K3	13
3	Discuss in detail about the necessity of starters in DC motors.	CO1	K2	54
4	With neat sketch explain the working of 3 point starters	CO1	K3	56
5	Derive equation for back EMF in DC motors	CO1	K5	43
6	Discuss the various types of dc generators with neat diagram and write the voltage equation for all types.	CO1	K2	22
7	Derive equation for torque of a dc motor	CO1	K5	51
8	Explain different types of DC Motors according to the excitation method.	CO1	K2	46
9	Explain about the back emf as regulating mechanism in DC Motors	CO1	K2	44
10	With neat sketch explain the power flow diagram of a generator.	CO1	K4	57
11	Explain back EMF and write the Back EMF equation for DC Motors.	CO1	K2	43

12	With neat sketch explain the power flow diagram of a motor.	CO1	K2	64
13	Investigate the load and open circuit characteristics of DC generators	CO1	K5	28
14	Investigate working principle of DC motors.	CO1	K5	37
MODULE II				
1	Define slip and justify at which time the slip should be maximum in 3 phase induction motors	CO2	K2	112
2	Elucidate in detail about the construction and types of single phase transformers	CO2	K4	73
3	Discuss the various methods of starting squirrel cage induction motors	CO2	K2	104
4	Derive EMF equation of the transformers	CO2	K5	79
5	Investigate the construction of three phase induction motors and classify its types.	CO2	K5	103
6	Elucidate in detail about short circuit and open circuit test of transformers	CO2	K3	98
7	Investigate the torque slip characteristics of 3 phase induction motors	CO2	K5	116
8	Compare squirrel cage and slip ring induction motor	CO2	K4	103
9	Discuss in detail about the basic working principle of three phase induction motors.	CO2	K2	111
10	Narrate the properties of ideal transformer. Sketch its phasor diagram	CO2	K3	86
11	Briefly explain the losses in a transformer.	CO2	K2	84

12	Explain in detail with necessary sketch the construction, working principle, emf equation, transformation ratio, and losses in a transformer.	CO2	K2	73
13	Explain any four starting methods of three phase induction motors.	CO2	K2	117
MODULE III				
1	Discuss the types of single phase induction motors	CO3	K3	129
2	Discuss the basic working principle behind the single phase induction motors	CO3	K3	126
3	With neat sketch discuss about the capacitive start and capacitive runt type induction motors	CO3	K2	131
4	Discuss in detail about double revolving field theory	CO3	K3	126
5	Investigate the concept of double revolving field theory and its application in the working of single phase induction motors.	CO3	K5	126
6	Discuss the various starting methods of single phase induction motors	CO3	K3	129
7	Why a single phase induction motor is not self-starting? How it can be made self-starting	CO3	K2	129
8	Compare capacitive start and capacitive run induction motors and mention its applications.	CO3	K5	131
9	Investigate the basic working principle behind the single phase induction motors	CO3	K5	126
10	Briefly explain different types of rotors of an alternator.	CO3	K2	135
11	Derive emf equation of an alternator.	CO3	K5	147
12	Explain the emf method to find the voltage regulation of an alternator.	CO3	K2	152

13	Numerate the steps with necessary equation for finding voltage regulation of alternator using synchronous impedance method.	CO3	K1	153
MODULE IV				
1	Briefly explain different types of stepper motor.	CO4	K2	161
2	Explain the concept of SCR with symbol	CO4	K1	180
3	Briefly explain about universal motor.	CO4	K2	157
4	Sketch V-I characteristics of SCR	CO4	K3	187
5	Explain the working principle of a synchronous motor.	CO4	K1	175
6	Explain the basic concept of a rectifier circuit.	CO4	K2	167
7	With neat sketch explain the working principle of servomechanisms, and mention its components role in mechanism.	CO4	K3	150
8	Explain different modes of operation of SCR	CO4	K3	183
9	With necessary circuit diagram and wave form explain single phase half-wave controlled rectifier with R load	CO4	K2	187
10	Explain the basic working principle and different types of stepper motor.	CO4	K2	161
11	With necessary circuit diagram and wave form explain single phase fully controlled bridge rectifier with R load	CO4	K2	194
12	Explain the construction and working principle of universal motor with necessary sketches.	CO4	K3	157
13	Investigate servomechanism and the working of servo motors.	CO4	K5	170

14	List the various applications of Servo motors and Stepper Motors.	CO4	K2	170
15	Compare Stepper Motor and Servo Motor.	CO4	K4	170
16	Justify the role of servo mechanisms in Robotics applications.	CO4	K5	170
MODULE V				
1	Compare conventional drives and modern drives	CO5	K4	204
2	With neat block diagram , explain the various components in the modern electric drives.	CO5	K2	204
3	Write the Fundamental torque equation and explain its components.	CO5	K3	209
4	Numerate the components of load torque.	CO5	K2	210
5	State essential parts of an electrical drive. What are the functions of a power modulator?	CO5	K3	204
6	Briefly explain a note on load equalization.	CO5	K2	223
7	What are the main factors which decide the choice of electrical drive for a given application?	CO5	K2	208
8	Briefly explain a note on load equalization.	CO5	K3	223
9	Briefly explain a note on steady state stability	CO5	K3	217
10	With neat sketch explain the multi quadrant operation of electric drives.	CO5	K2	214
11	Investigate in detail about fundamental torque equations	CO5	K5	209
12	Explain in detail about three phase induction motor drives.	CO5	K2	226

13	Explain the speed torque convention and the multi quadrant operation of an electric drive with relevant diagrams.	CO5	K2	214

APPENDIX 1

CONTENT BEYOND THE SYLLABUS

MODULE 1

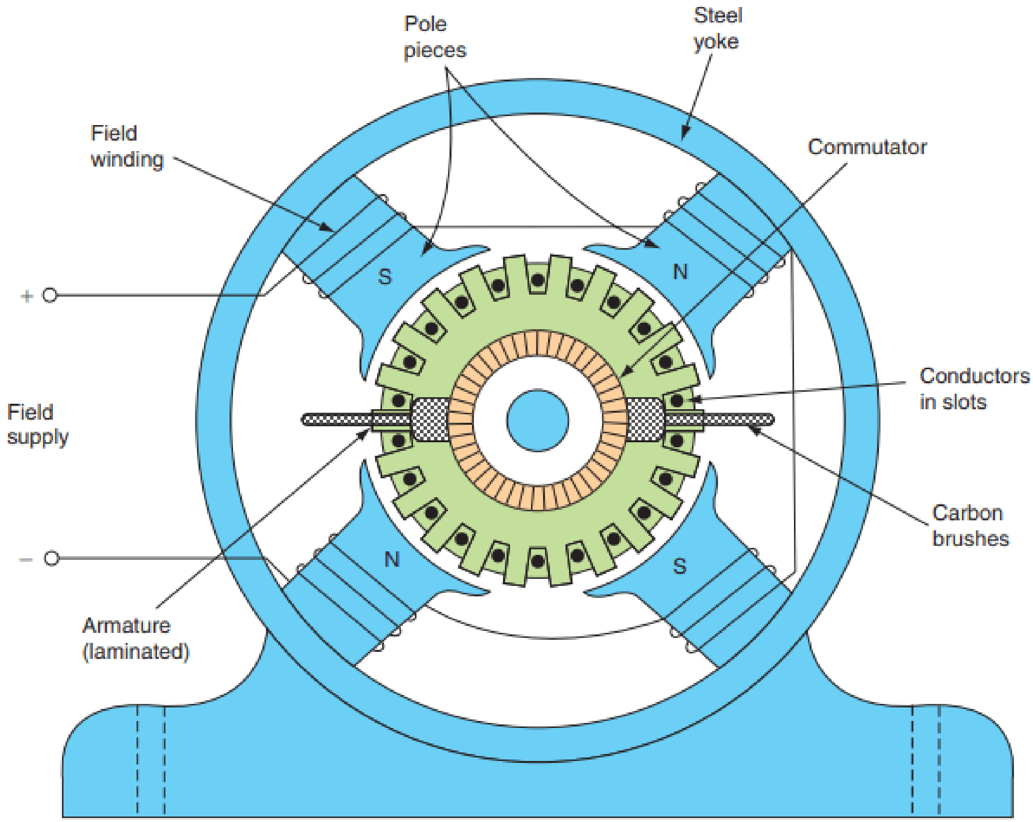
DC MACHINES

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.

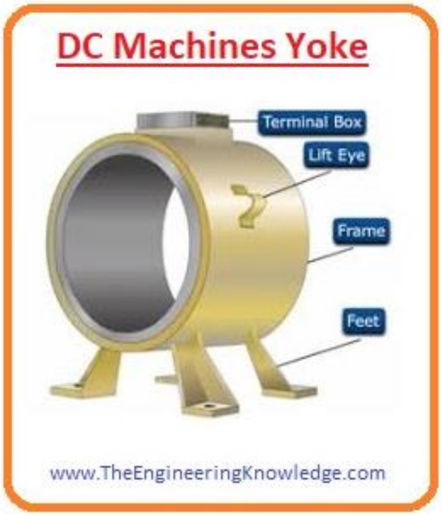
DC MACHINES CONSTRUCTION

- 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

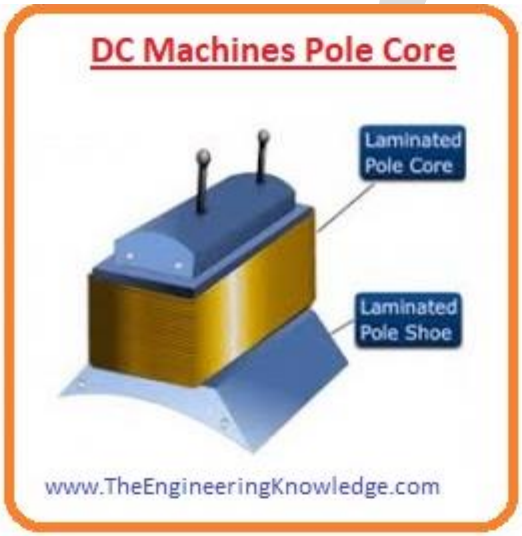
- The yoke of machines is also known as the frame, the main working of this part is to provide protection to the internal circuitry of a machine from the outer environment, temperature, moisture, and some other factors.
- This part of the machine is constructed with the cast steel and cast iron.



DC Machines Pole Core

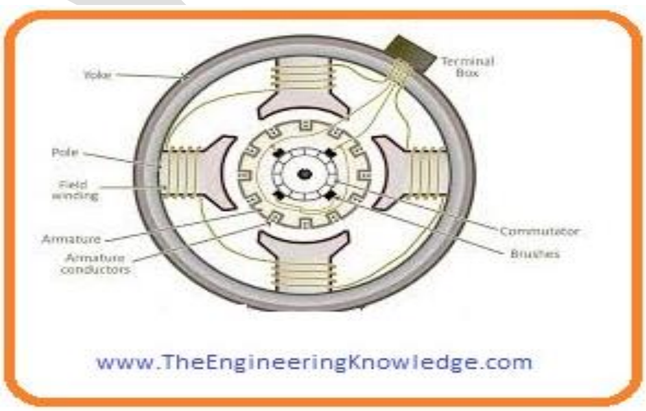
- At stator of the dc machines, the poles are of an electromagnet the windings on these poles are known as the field windings.
- The input provided at the stator connected with the field windings generate flux at the stator and make poles electromagnet.

These poles are constructed with cast steel, cast iron.



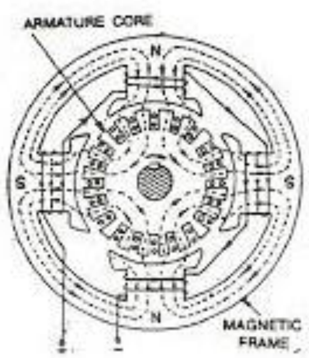
DC Machines Field Windings

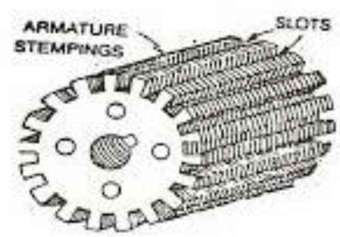
- These windings are wound at the sating part of machines on the poles at the stator. These windings are constructed with copper. The current provided at these windings generates flux and makes poles electromagnet.

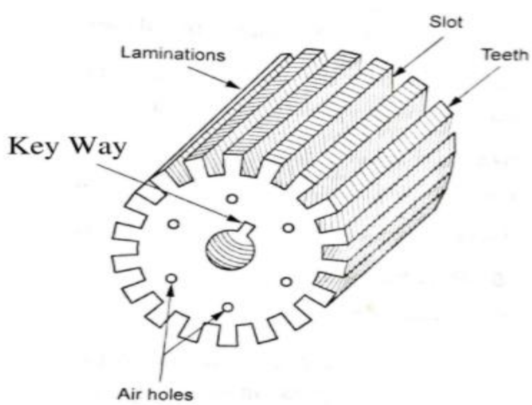


DC Machines Armature Core

- 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.

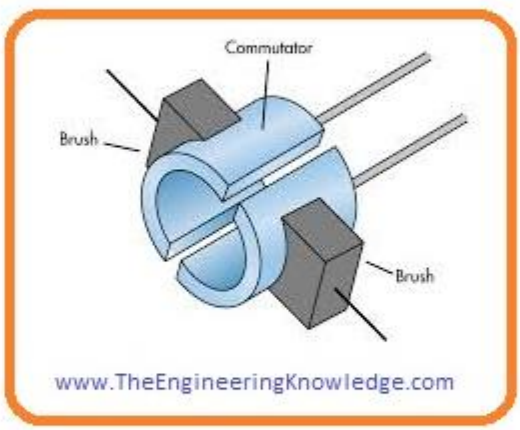
DC Machines Commutator

- 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.

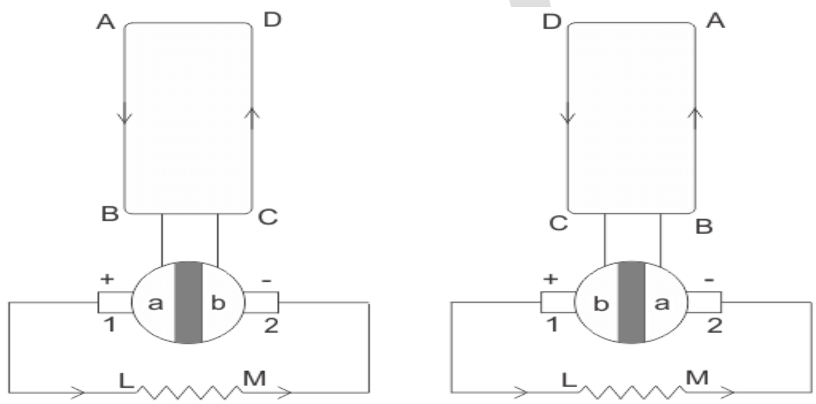


DC GENERATORS

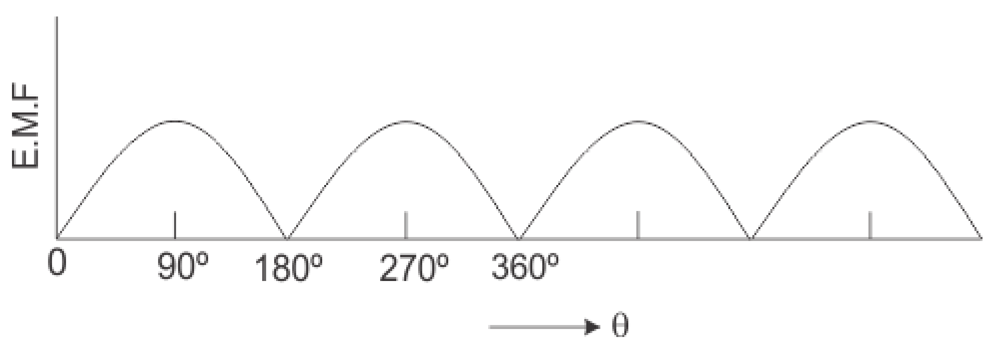
What is a DC Generator?

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

$$e = \frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \text{ volts} \quad \ldots\ldots(4)$$

The number of conductors connected in series in each parallel path = Z/A.

Therefore, the average induced e.m.f across each parallel path or the armature terminals is given by the equation shown below:

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

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

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

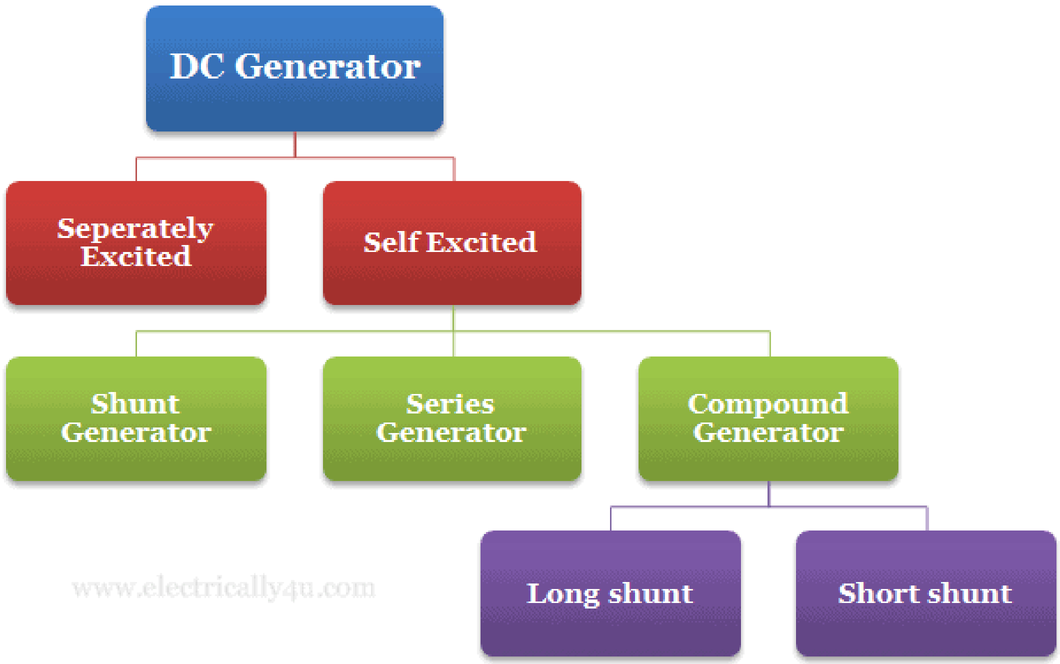
Here, number of parallel paths is equal to number of conductors in one path i.e. P = A

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

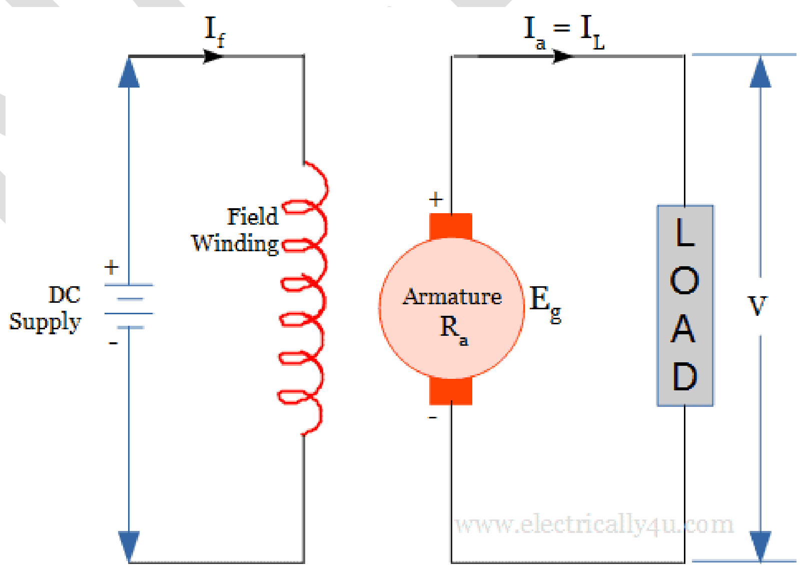
DC generators are classified based on the way in which the field windings are excited. The different types of DC generator are shown below



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.

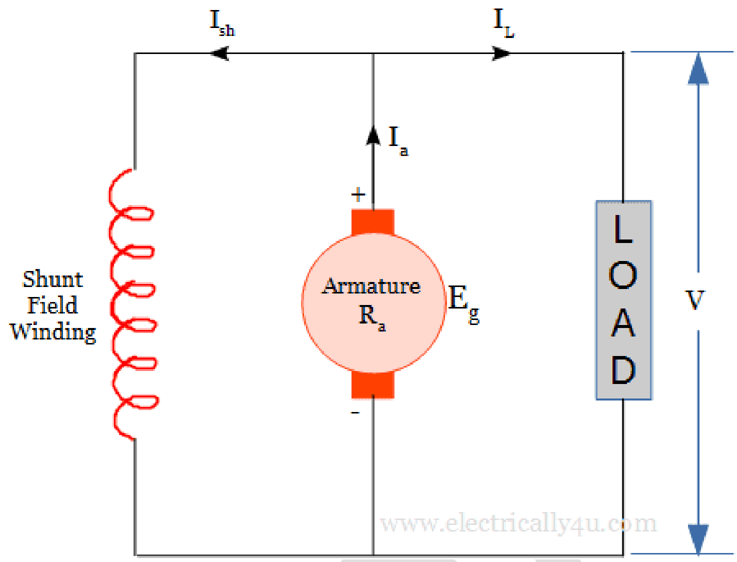
There are three types of self-excited DC generator based on the way, in which the field coils and armature are connected. They are

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, $V = E_g – I_a R_a – V_{br}$

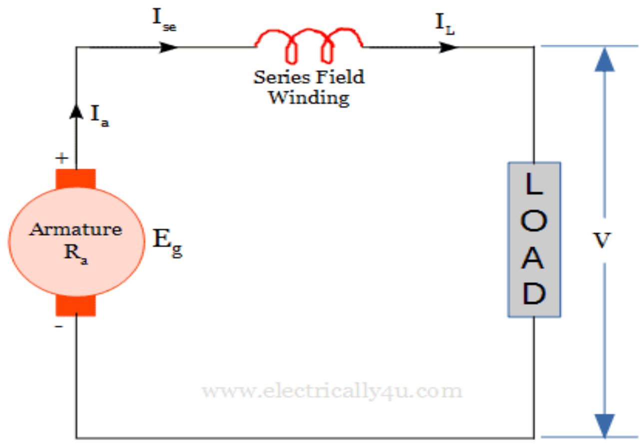
Power developed in the DC generator = $E_g I_a$

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

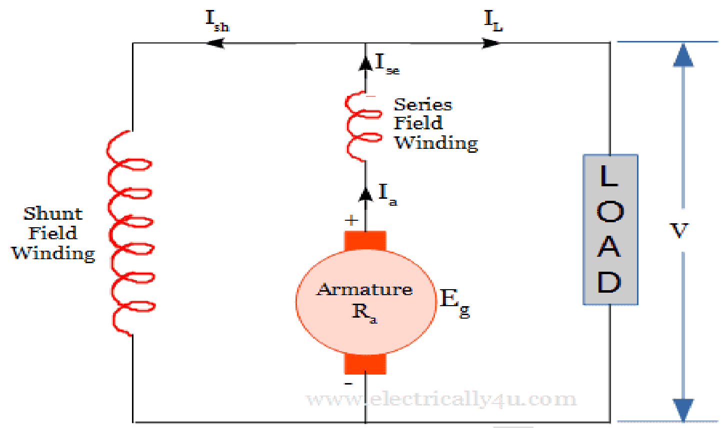
DC compound generator has both shunt field winding and series field winding. One field winding is connected in series with the armature and another field winding is connected in parallel with the armature.

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

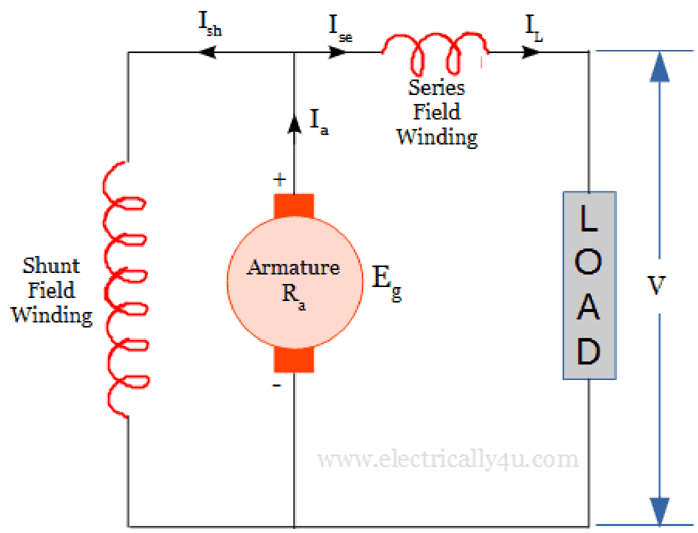
Terminal voltage equation is given by, $V = E_g – I_a R_a – I_a R_{se} – V_{br}$

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

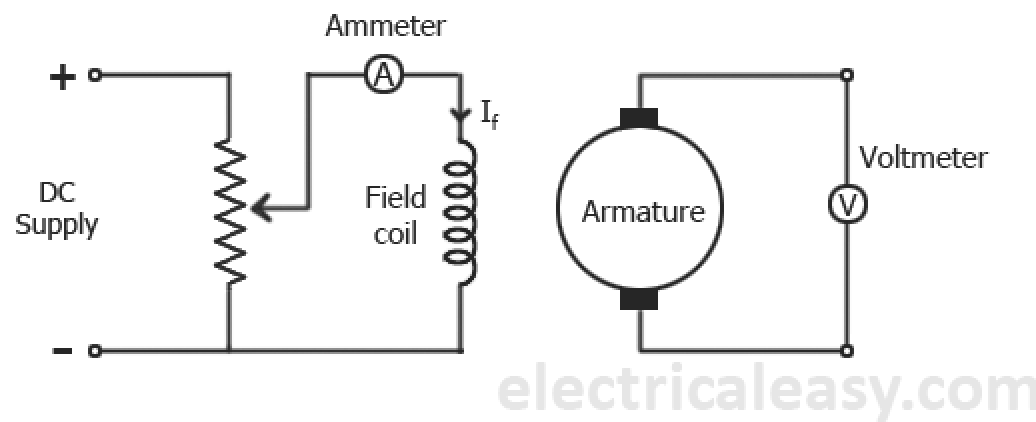
CHARACTERISTICS OF DC GENERATORS

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.

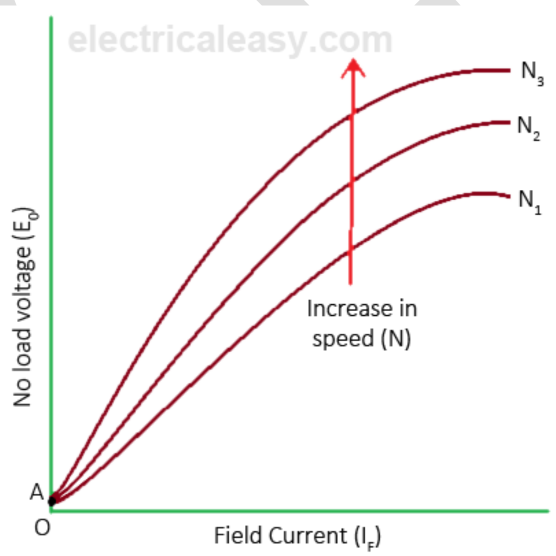
These **characteristics of DC generators** are explained below.

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.



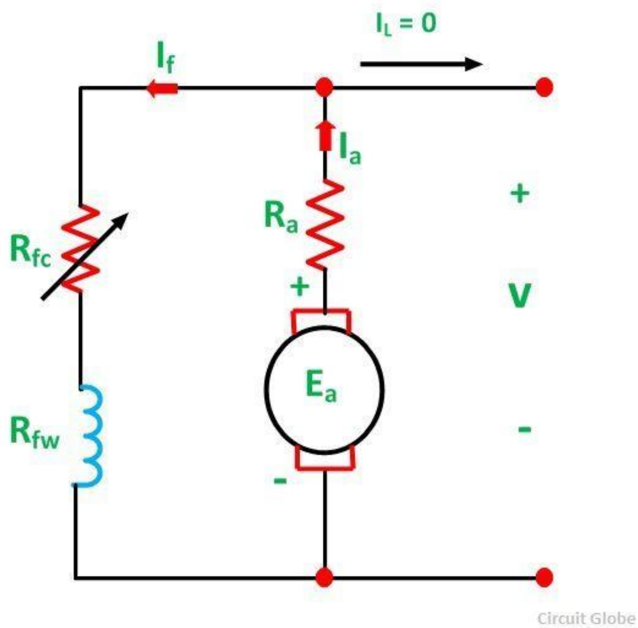
Open Circuit Characteristic (O.C.C.)

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.

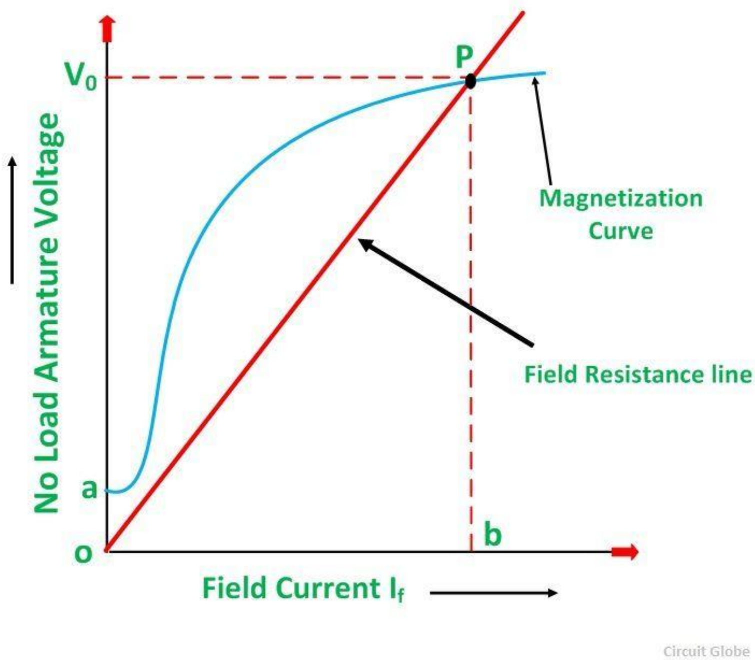
$$E_{ar} = K\varphi_{res}\omega$$

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.

$$I_a = I_f$$

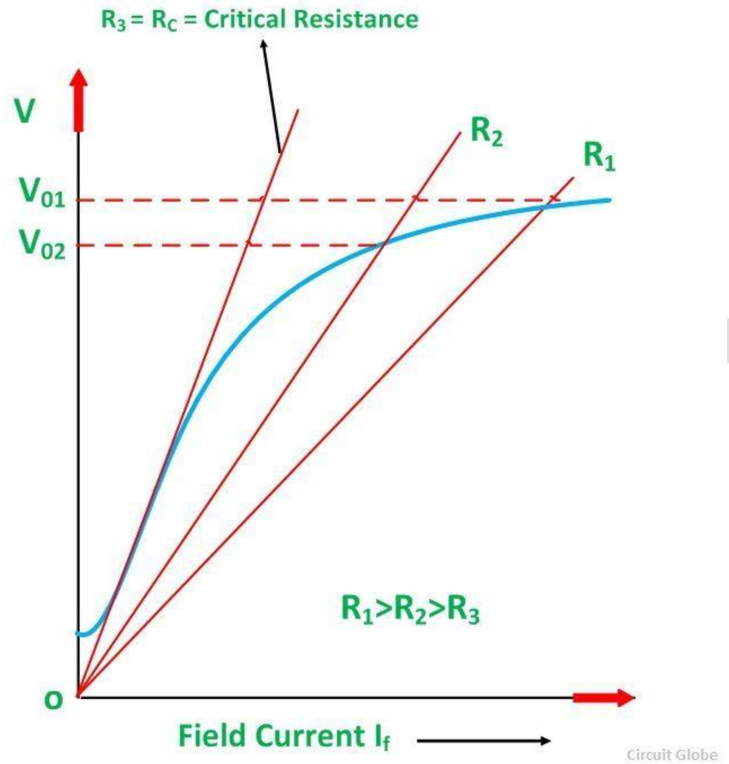
$$V = E_a - I_aR_a = E_a - I_fR_a \ldots\ldots\ldots(1)$$

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:

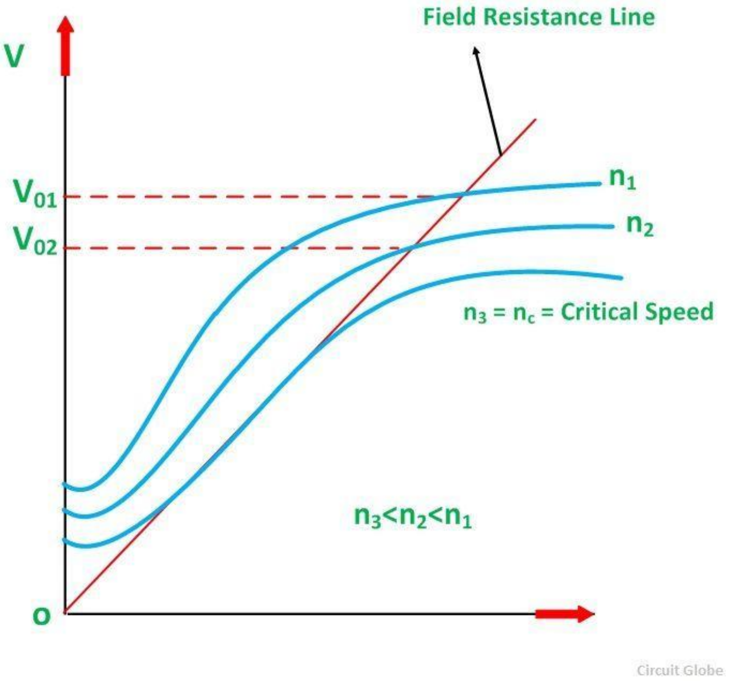


Effect of Field Resistance on No-Load Voltage

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)

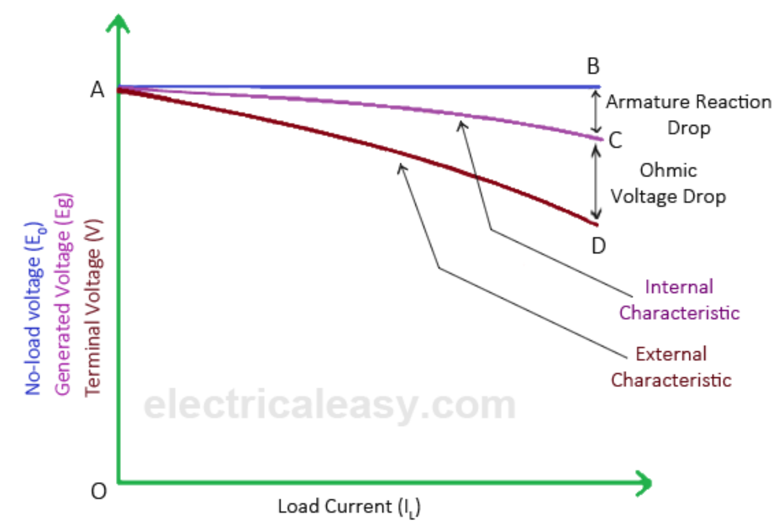
An internal characteristic curve shows the relation between the on-load generated emf (Eg) and the armature current (I_a). The on-load generated emf Eg is always less than E_0 due to the armature reaction. Eg can be determined by subtracting the drop due to demagnetizing effect of armature reaction from 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



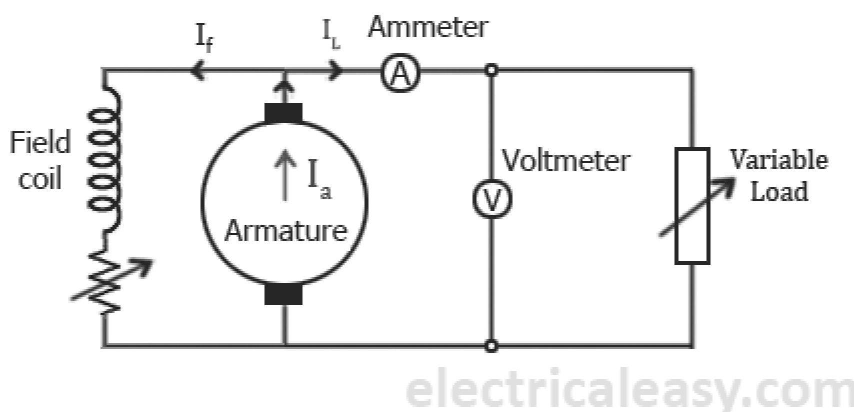
Characteristics of separately excited DC generator

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.

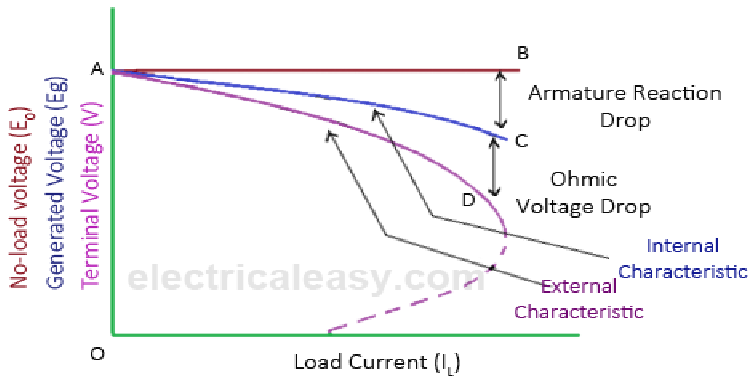
load current I_L. Due to the demagnetizing effect of armature reaction, the on-load generated emf is less than the no-load voltage. The curve AC represents the on-load generated emf Eg vs. load current I_L i.e. internal characteristic (as $I_a = I_L$ for a separately excited dc generator). Also, the 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.



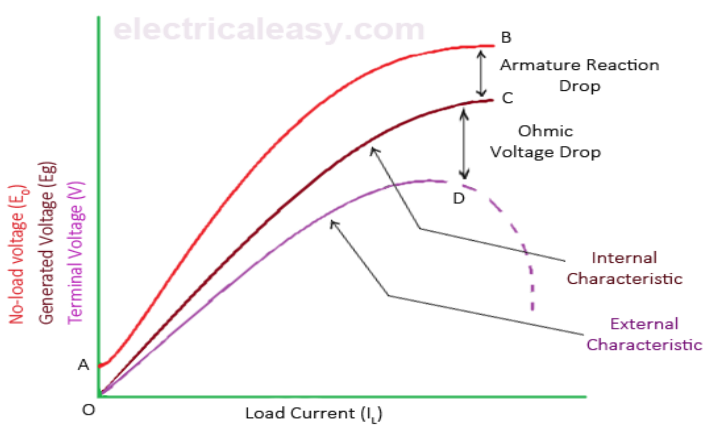
Unlike, separately excited DC generator, here, $I_L \neq I_a$. For a shunt generator, $I_a = I_L + I_f$. Hence, the internal characteristic can be easily transmitted to Eg vs. I_L by subtracting the correct value of I_f from I_a.



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.

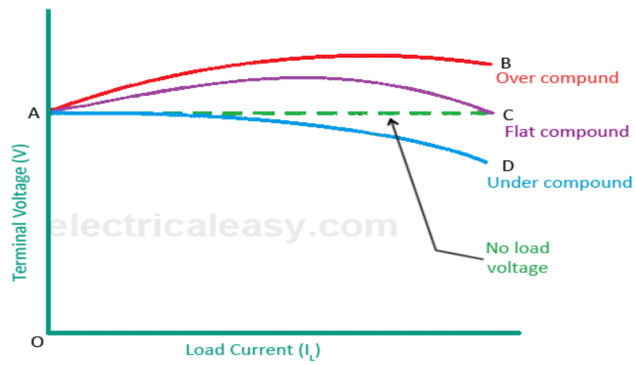
Characteristics Of DC Series Generator



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.

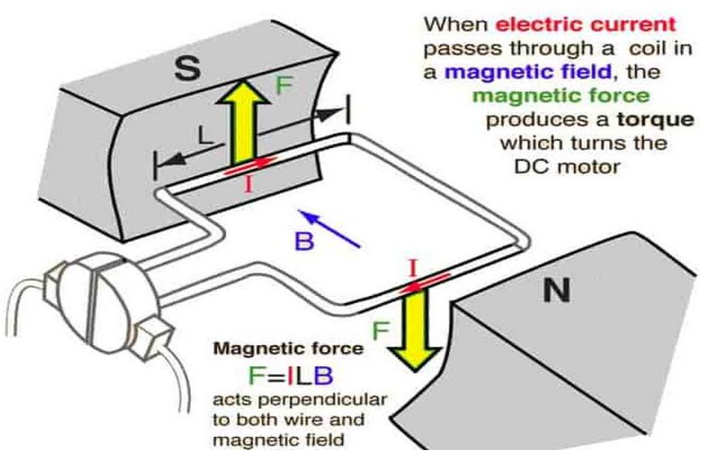
DC motor working is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.

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.

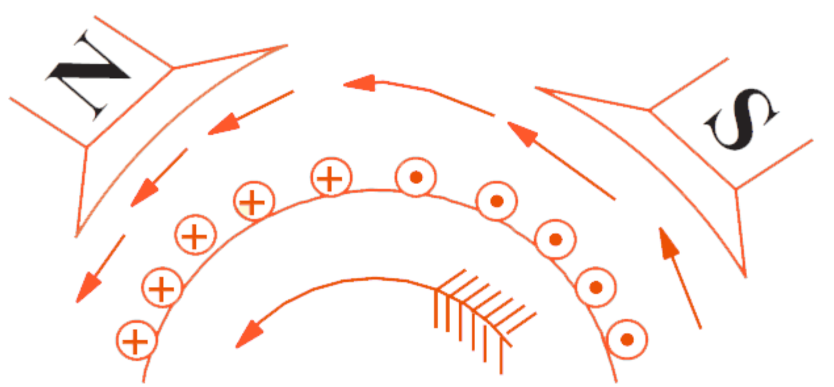


Basically, there is no constructional difference between a DC motor and a DC generator. The same DC machine can be run as a generator or motor.

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.

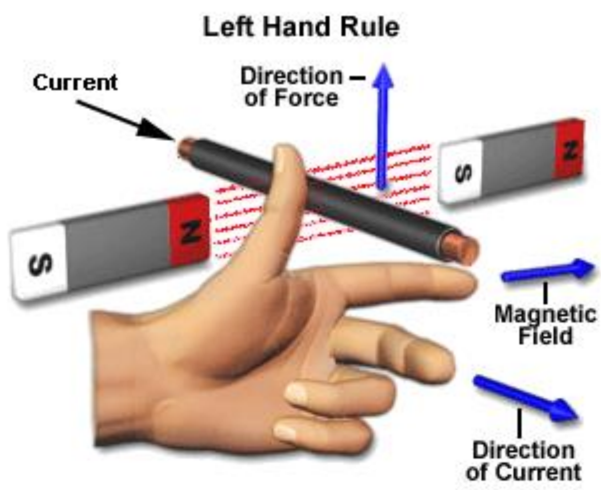


All conductors under North-pole carry currents in one direction while all the conductors under South-pole carry currents in the opposite direction.

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**.

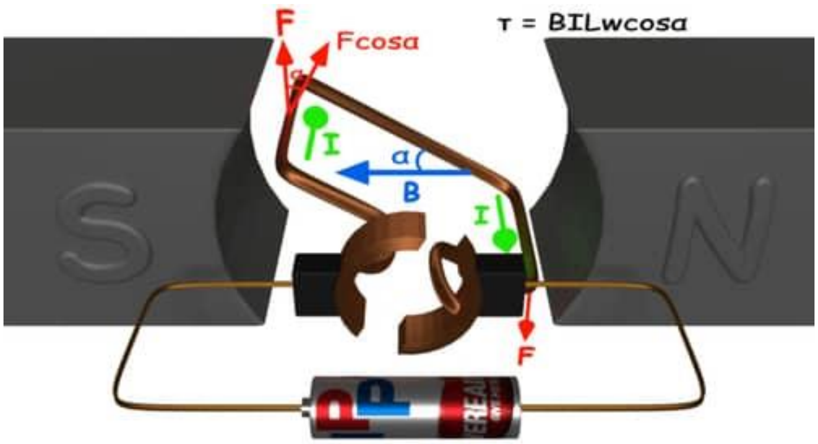
The torque produced is given by,

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

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

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

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.



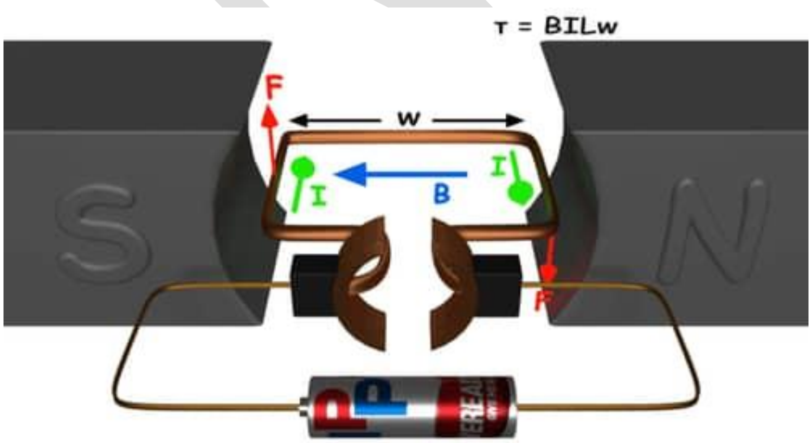
Step 1:

Initially considering the armature is in its starting point or reference position where the angle

α =0.

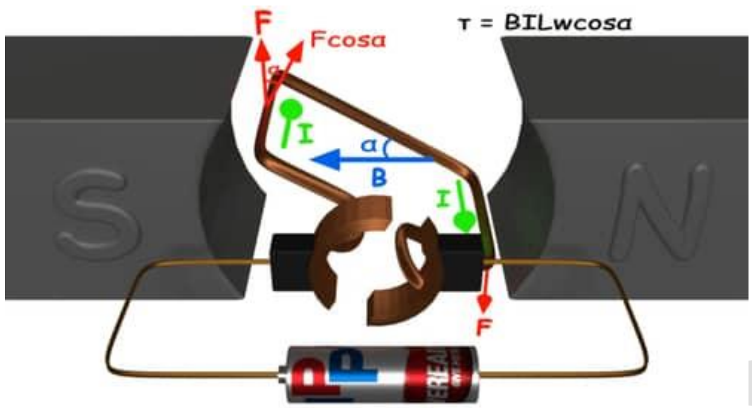
$$\therefore\ \tau = BILw \times \cos 0^{\circ} = BILw$$

Since, $\alpha = 0$, the term $\cos \alpha = 1$, or the maximum value, hence torque at this position is maximum given by τ = BILw. This high starting torque helps in overcoming the initial inertia of rest of the armature and sets it into the rotation.



Step 2:

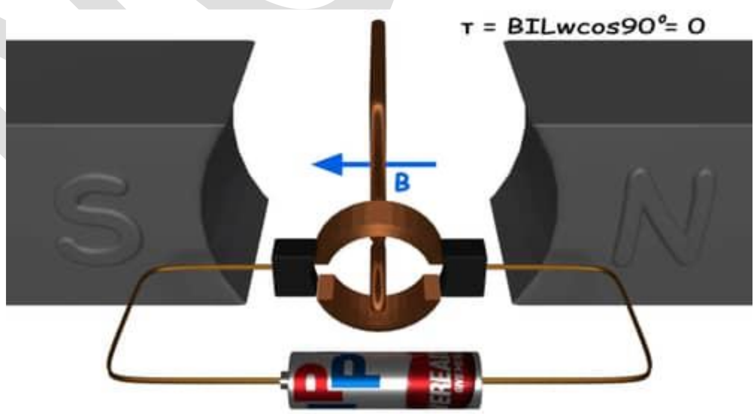
Once the armature sets in motion, the angle α between the actual position of the armature and its initial reference position goes on increasing in the path of its rotation until it becomes 90^o from its initial position. Consequently, the term cosα decreases and also the value of torque. The torque in this case is given by τ = BILwcosα which is less than BIL w when α is greater than 0^o.



Step 3:

In the path of the rotation of the armature a point is reached where the actual position of the rotor is exactly perpendicular to its initial position, i.e. $\alpha = 90^o$, and as a result the term cosα = 0. The torque acting on the conductor at this position is given by,

$$\therefore \tau = BIL\omega \times \cos 90^o = 0$$



i.e. virtually no rotating torque acts on the armature at this instance. But still the armature does not come to a standstill, this is because of the fact that the **operation of DC motor** has been engineered in such a way that the inertia of motion at this point is just enough to overcome this point of null torque. Once the rotor crosses over this position the angle between the actual position of the armature and the initial plane again decreases and torque starts acting on it again.

BACK EMF IN DC MOTOR

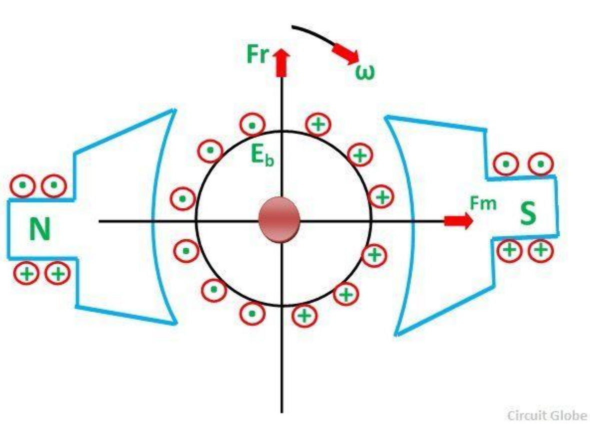
When the current-carrying conductor placed in a magnetic field, the torque induces on the conductor, the torque rotates the conductor which cuts the flux of the magnetic field. According to the Electromagnetic Induction Phenomenon "when the conductor cuts the magnetic field, EMF induces in the conductor"

The Fleming right-hand rule determines the direction of the induced EMF.

According to Fleming Right Hand Rule, if we hold our thumb, middle finger and index finger of the right hand by an angle of 90°, then the index finger represents the direction of the magnetic field. The thumb shows the direction of motion of the conductor and the middle finger represents the emf induces on the conductor.

On applying the right-hand rule in the figure shown below, it is seen that the direction of the induced emf is opposite to the applied voltage. Thereby the emf is known as the *counter emf or back emf*.

The back emf is developed in series with the applied voltage, but opposite in direction, i.e., the back emf opposes the current which causes it.

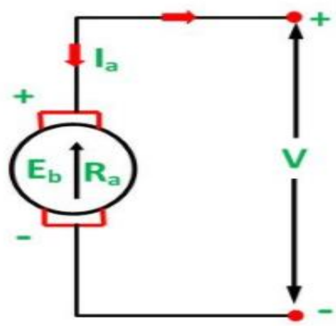


The magnitude of the back emf is given by the same expression shown below:

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

Where E_b is the induced emf of the motor known as Back EMF, A is the number of parallel paths through the armature between the brushes of opposite polarity. P is the number of poles, N is the speed, Z is the total number of conductors in the armature and ϕ is the useful flux per pole.

A simple conventional circuit diagram of the machine working as a motor is shown in the diagram below:



In this case, the magnitude of the back emf is always less than the applied voltage. The difference between the two is nearly equal when the motor runs under normal conditions.

The current induces on the motor because of the main supply. The relation between the main supply, back emf and armature current is given as $E_b = V – I_aR_a$.

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

$$P_m = VI_a - 2I_aR_a$$

$$\frac{dP_m}{dI_a} = VI_a - 2I_aR_a$$

$$VI_a - 2I_aR_a = 0$$

$$V = 2I_aR_a$$

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

On differentiating the above equation we get

From the back emf equation, we get

$$V = E_b + I_aR_a$$

On substituting the I_aR_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.

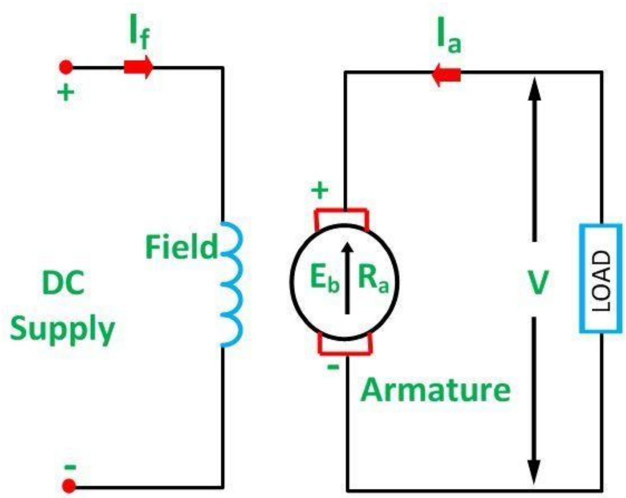
The dc motor converts electrical power into mechanical power. The construction of the dc motor and generator are the same. But the dc motor has a wide range of speed and good speed regulation in electric traction.

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:



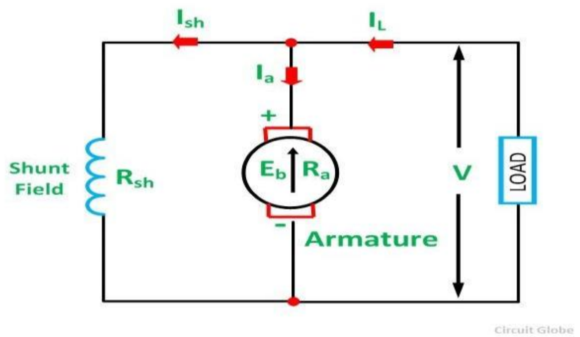
Separately Excited DC Motor

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:

$$V = E + I_a R_a \;\ldots\ldots\ldots (3)$$

The power equation is given as:

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

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

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

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

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

$$P_m = EI_a \;\ldots\ldots\ldots (5)$$

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

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

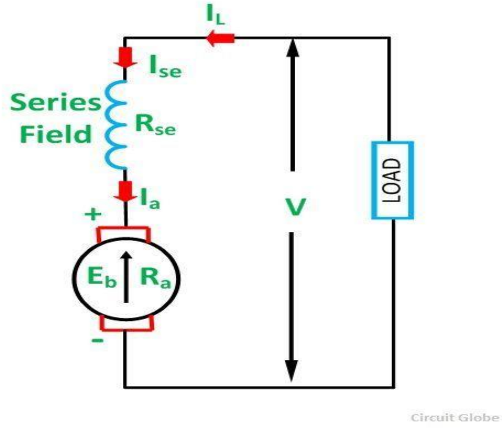
$$VI_a = P_m + I_a^2 R_a \;\ldots\ldots\ldots (7)$$

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

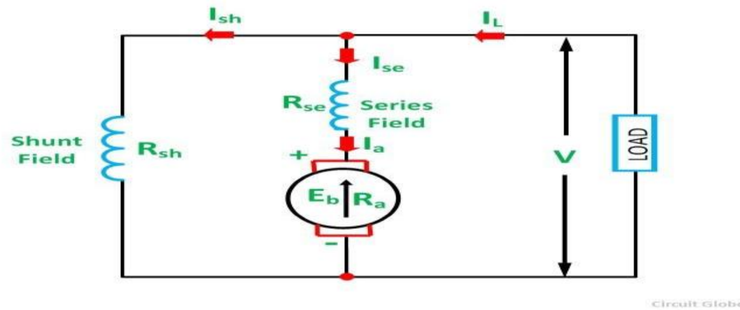
$$VI = P_m + I^2R_a + I^2R_a \dots\dots\dots (10)$$

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.

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

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:

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

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

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

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

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:

$$I_a = \frac{V - E}{R_a} \;\ldots\ldots\ldots\; (1)$$

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:

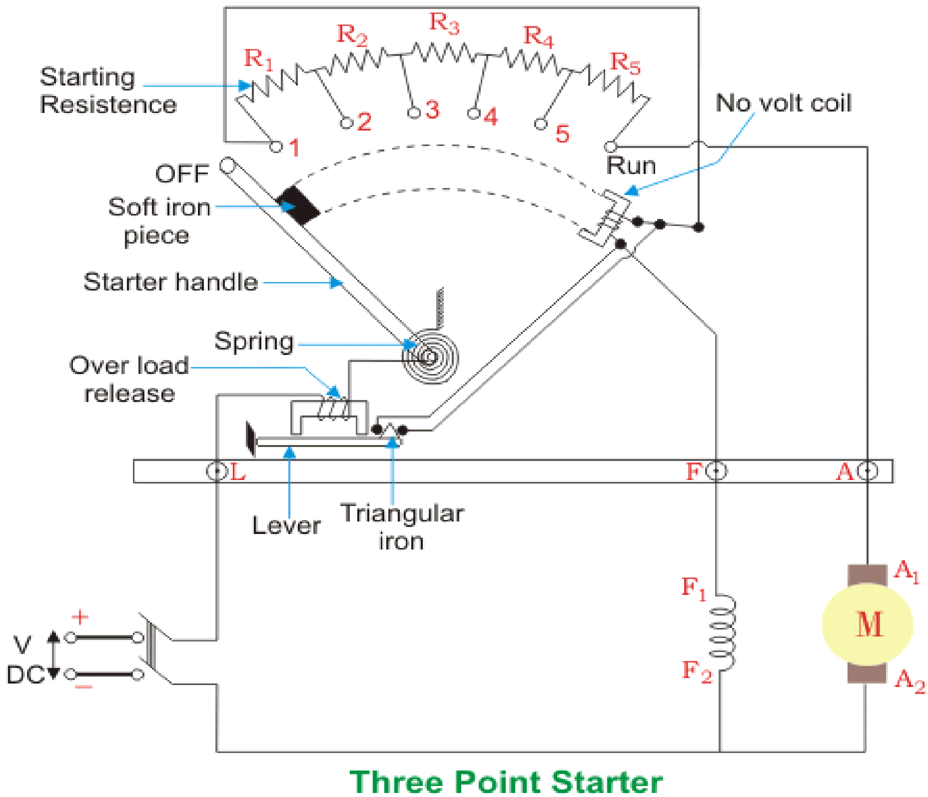
$$E = E_b + I_a . R_a$$

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.

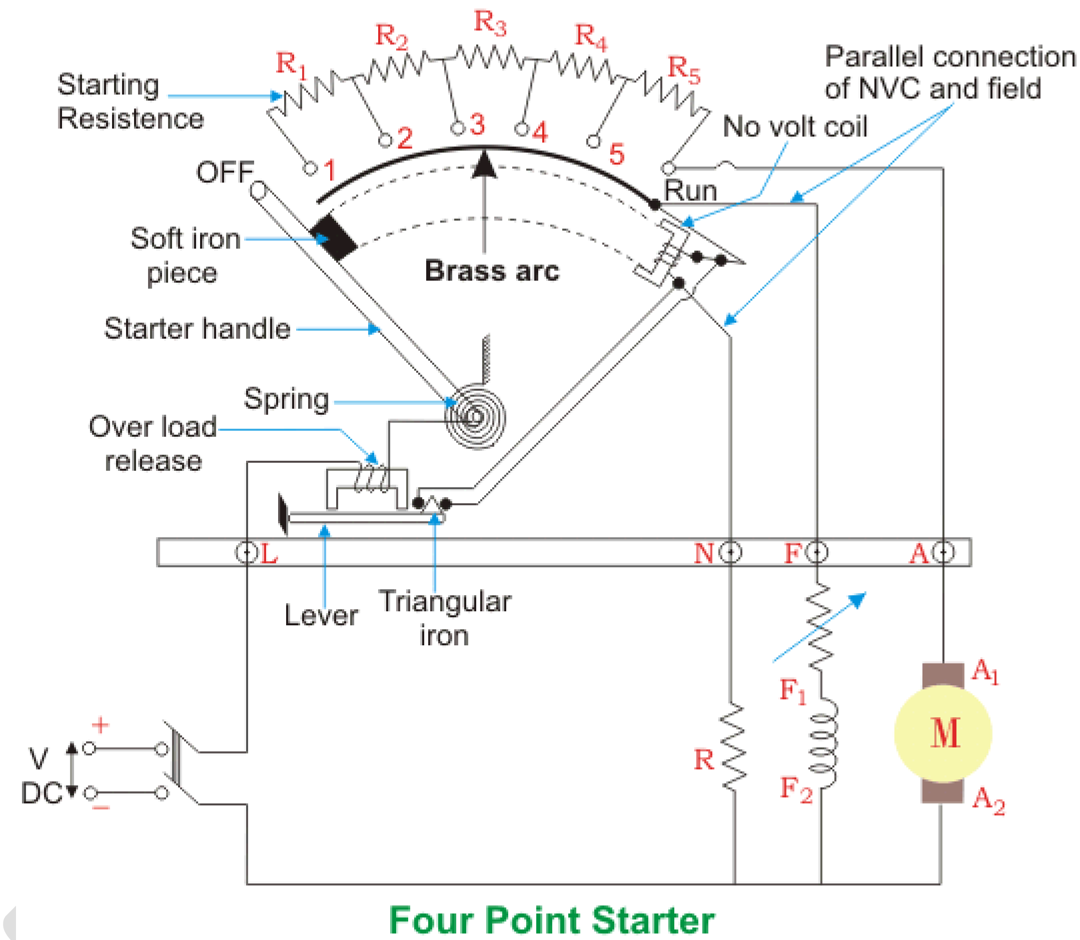
FOUR POINT STARTER

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.

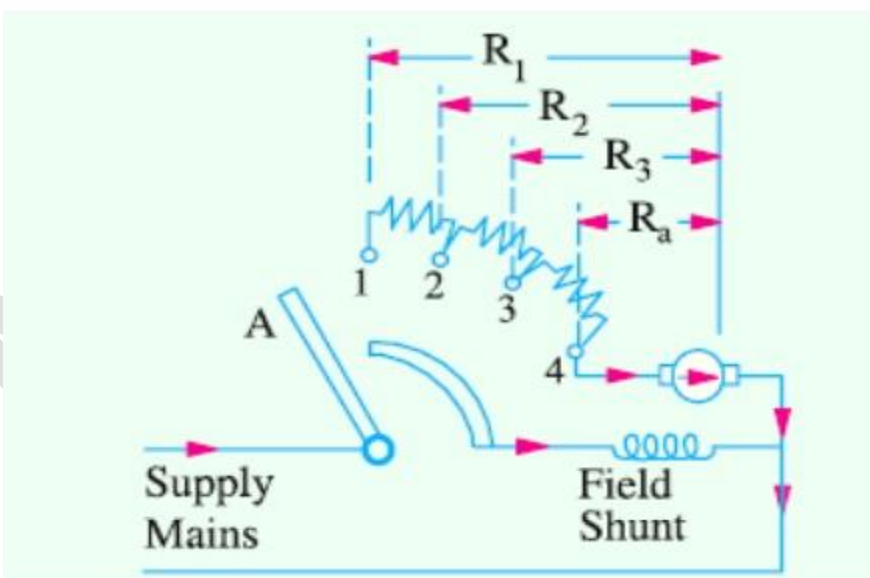


Fig 3.3 Two Point Starter

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.

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

- 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.

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

- 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.

$$\textbf{Armature winding losses} = P_A = I_A^2 R_A$$

$$\textbf{Field winding losses} = P_F = I_F^2 R_F$$

  - 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.

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

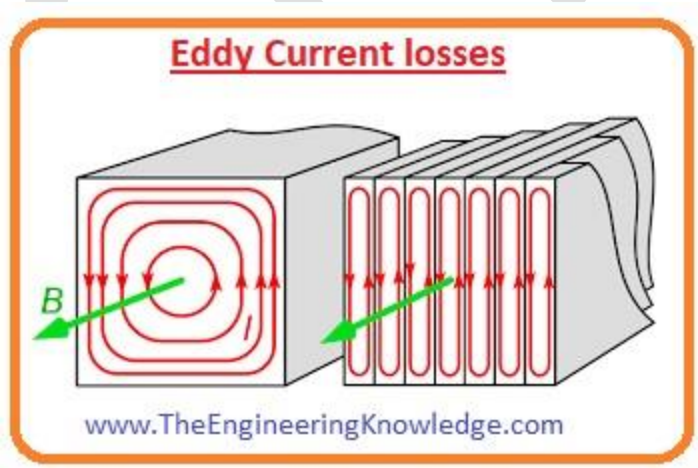
- In this equation.
- P_{BD} is the loss at the carbon brushes.
- V_{BD} voltage losses at the brushes.
- I_A is the armature current.
- The purpose that the brush losses are found in this way is that the voltage drop at the brushes remains same at the different values of currents.

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

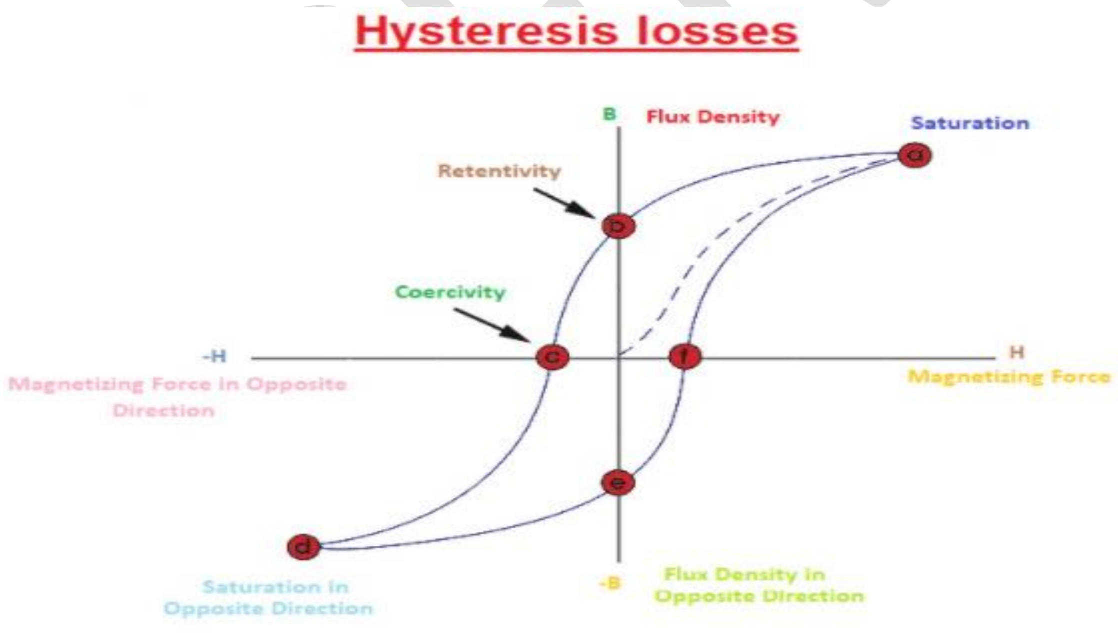
- If we apply this law on dc machine that we come to know that when the rotor of the machine rotates in the field of the rotor than voltage induces in the rotor that current starts to flow through the armature winding this current known as eddy current.
- The mathematical expression for these current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

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

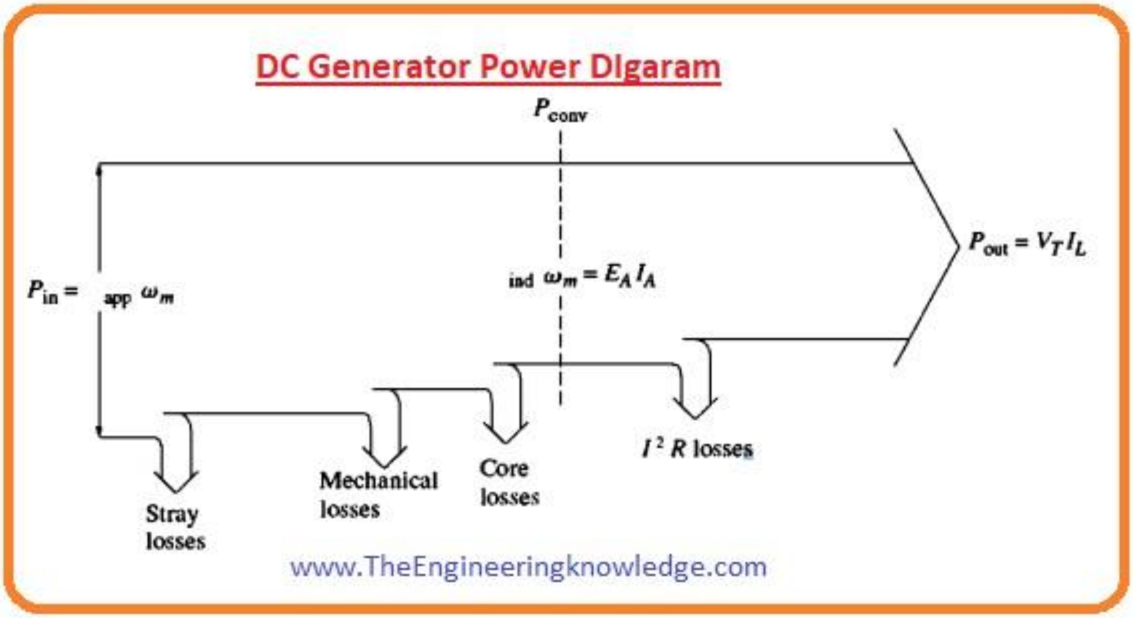
- In this equation.
- P_b denotes the hysteresis losses
- H is Steinmetz hysteresis coefficient. Its value is from 1.5 to 2.5l
- B_{max}^n is flux density.
- f is frequency.
- V is volume of material used for core construction.
- In the given figure, you can see the curve for these losses.

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.

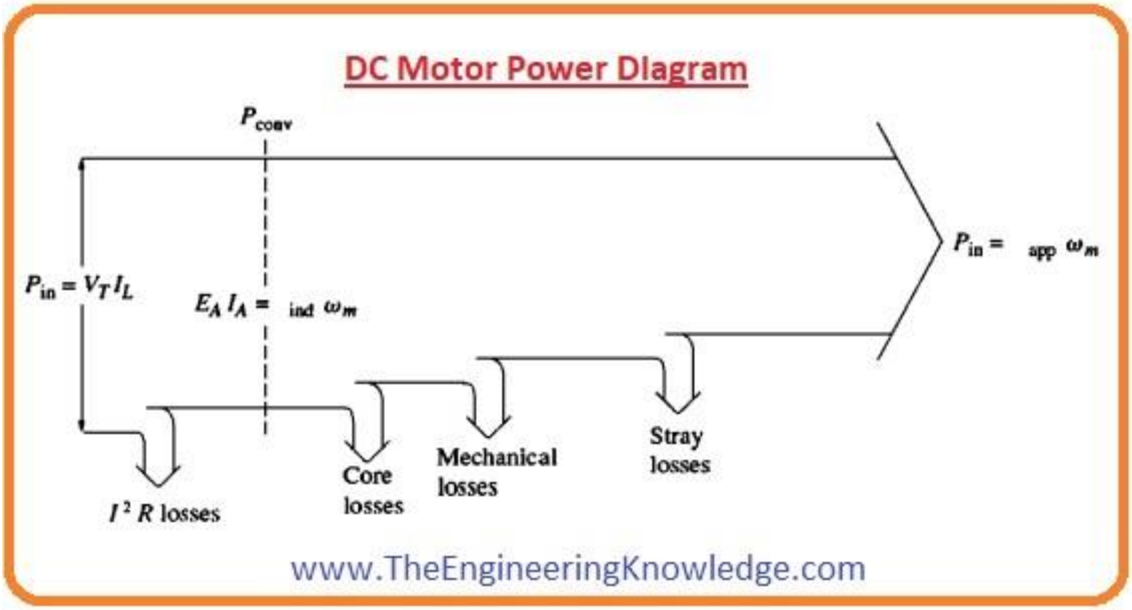
  Input as mechanical power.

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

  Output power is given here.

$$\mathbf{P_{conv}=E_AI_A}$$

- 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.


DC Motor Power Diagram
Pconv
Pin = VT IL
EA IA = ind ωm
Pin = app ωm
I2 R losses
Core losses
Mechanical losses
Stray losses
www.TheEngineeringKnowledge.com

MODULE II

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.

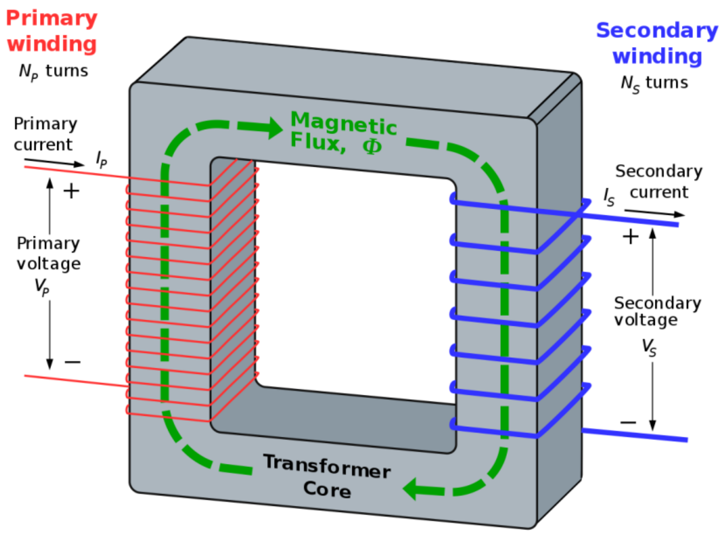
In a broad, transformers are categorized into two types, namely, electronic transformers and power transformers. Electronic transformers operating voltages are very low and are rated at low power levels. These are used in consumer electronic equipments like televisions, personal computers, CD/DVD players,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



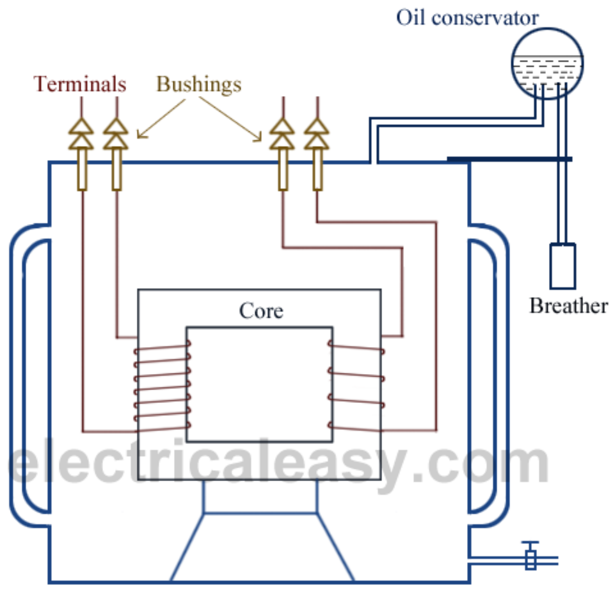
electric transformer

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.

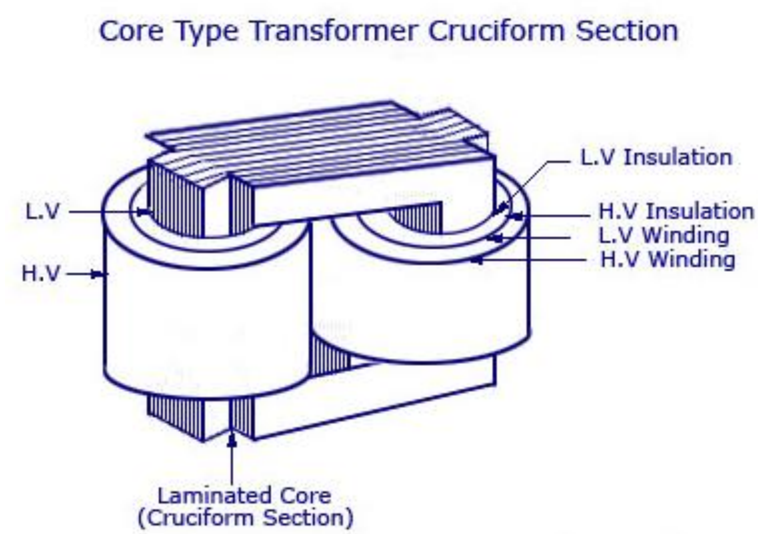
The thickness of these laminated sheets of steel are 0.35 to 5 mm and are insulated with a varnish, or oxide, or phosphate and then formed as a core.

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.

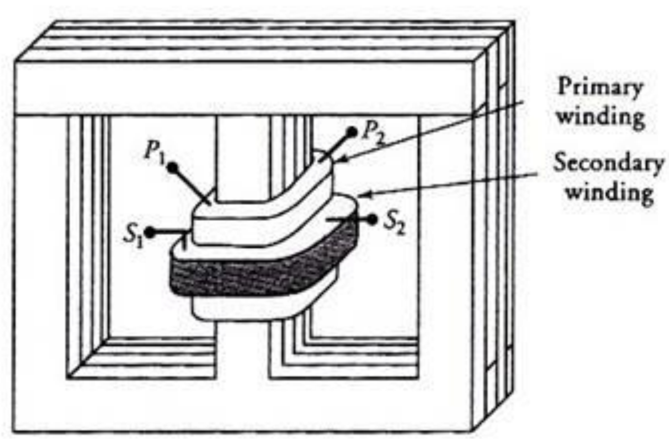
And for a large sized core type transformer, cruciform core with round or circular cylindrical coils are used. In most of the core type transformers, cylindrical coils are used due to their mechanical strength. These cylindrical coils are wound in helical layers and are insulated from each other by insulating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

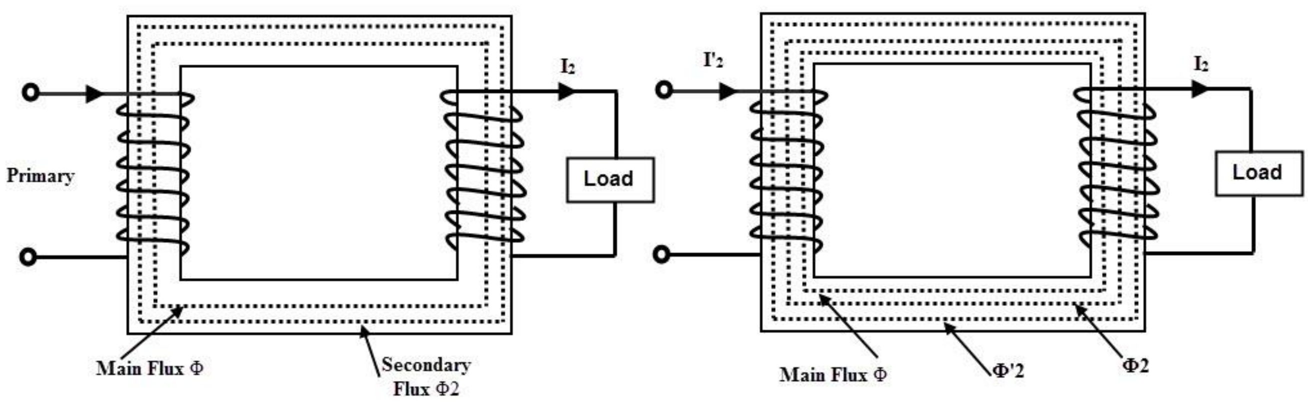
The operation of the transformer is based on the principle of mutual induction between two coils or winding which are linked by a common magnetic flux. When the primary winding is energized with AC source supply, a magnetic flux is established in the primary winding.

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

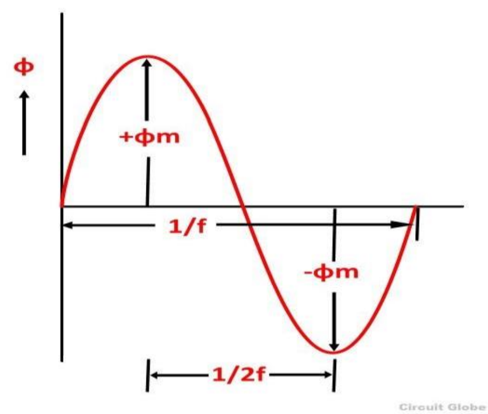
When a sinusoidal voltage is applied to the primary winding of a transformer, alternating flux ϕ_m sets up in the iron core of the transformer. This sinusoidal flux links with both primary and secondary winding. The function of flux is a sine function.

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 $\Psi = N_1\phi$

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

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

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

$$E_1 = -N_1 w\varphi_m \text{Coswt}$$

$$E_1 = N_1 w\varphi_m \text{Sin}(wt - \pi/2) \ldots\ldots\ldots(3)$$

So the induced emf lags flux by 90 degrees.

Maximum valve of emf

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

But $w = 2\pi f$

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

Root mean square RMS value is

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

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

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

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

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

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.

$$E_1 I_1 Cos\text{ø} = E_2 I_2 Cos\text{ø}$$

$$\frac{E_1}{E_2} = \frac{I_2}{I_1}$$

$$\frac{E_1}{E_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

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

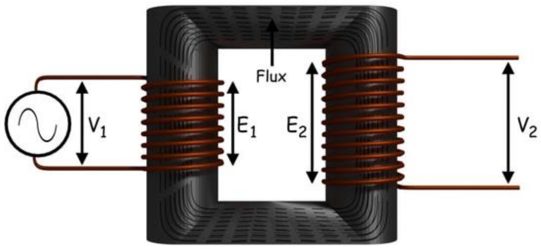
An **ideal transformer** is an imaginary transformer which has

- *no copper losses (no winding resistance)*

- *no iron loss in core*

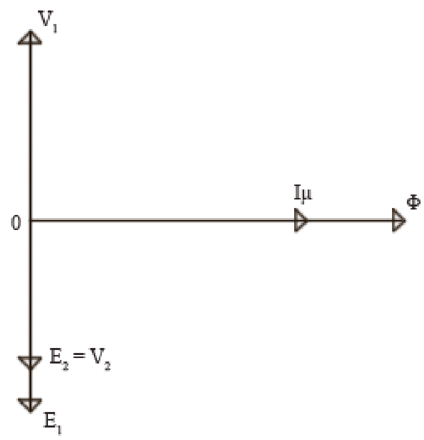
- *no leakage flux*

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.

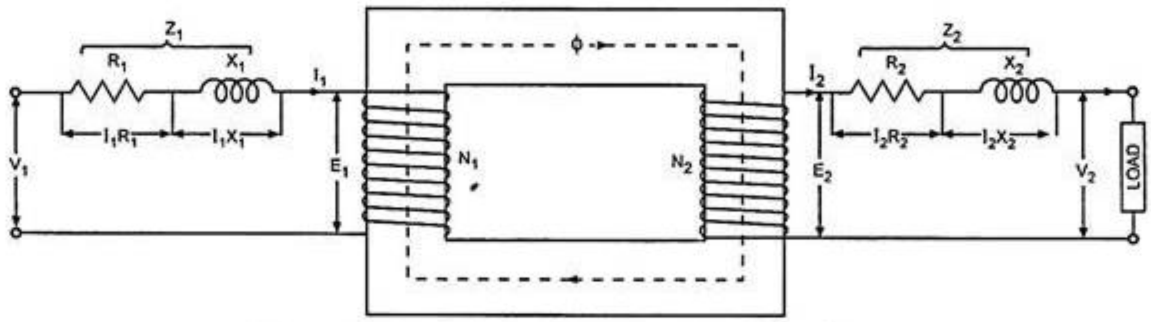


Now, if an alternating voltage V_1 is applied to the primary winding of an ideal transformer, counter emf E_1 will be induced in the primary winding. As windings are purely inductive, this induced emf E_1 will be exactly equal to the apply voltage but in 180 degree phase opposition. Current drawn from 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 Iμ. This magnetizing current Iμ 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, $E_1 I_1 = E_2 I_2$.

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 $Z_2 = R_2 + jX_2$.



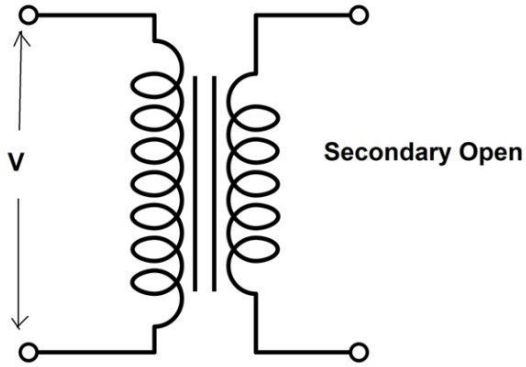
An Equivalent Diagram of Actual Transformer

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:

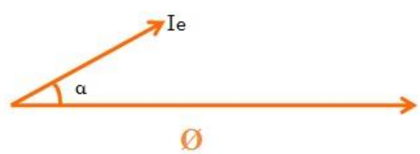
Transformer at no load means that its secondary winding is open and primary is energized from voltage source. Figure below shows this condition.



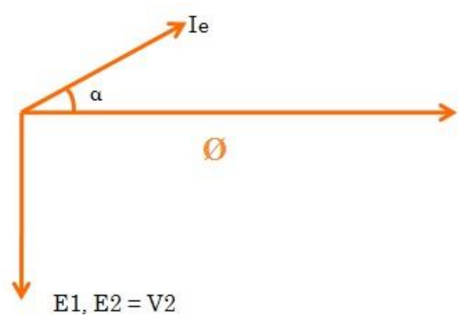
Following steps should be followed for phasor diagram of transformer at no load condition:

- Working Flux Ø taken as Reference as shown below.

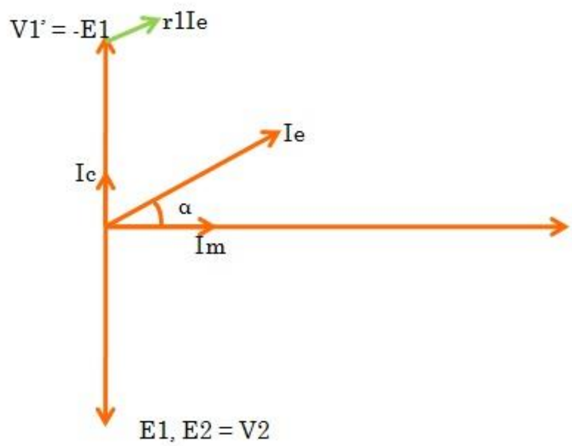
- Excitation Current I_e leading Ø by α.



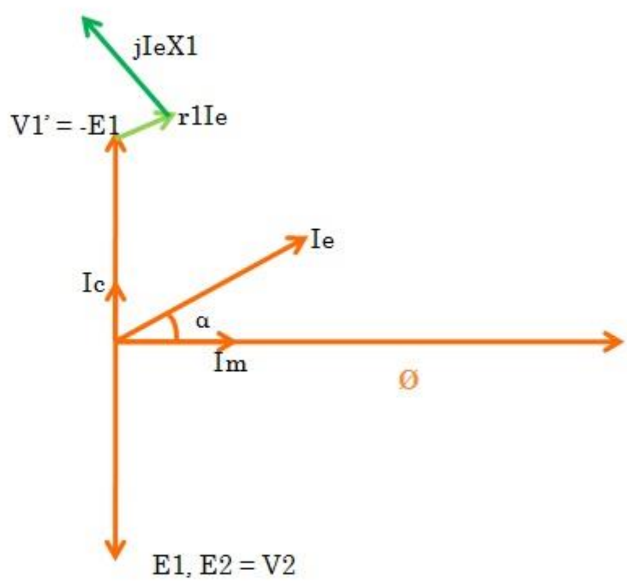
- Induced EMF E_1 and E_2 lagging Flux by 90 degree.



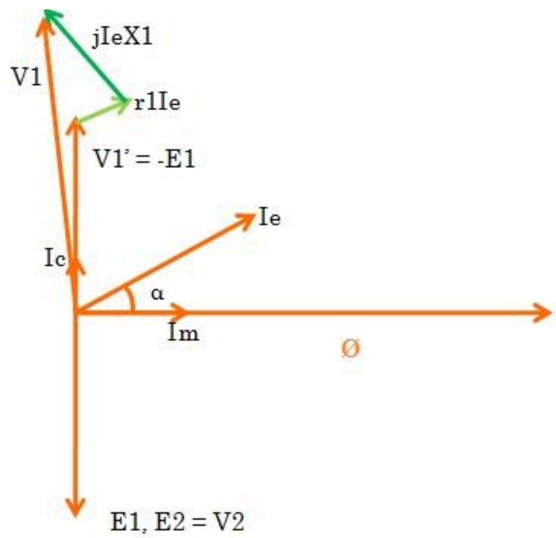
- Voltage drop $r_1 I_e$ in Primary. This will be in phase with the I_e and hence shown parallel to it in the figure below.



- 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.)



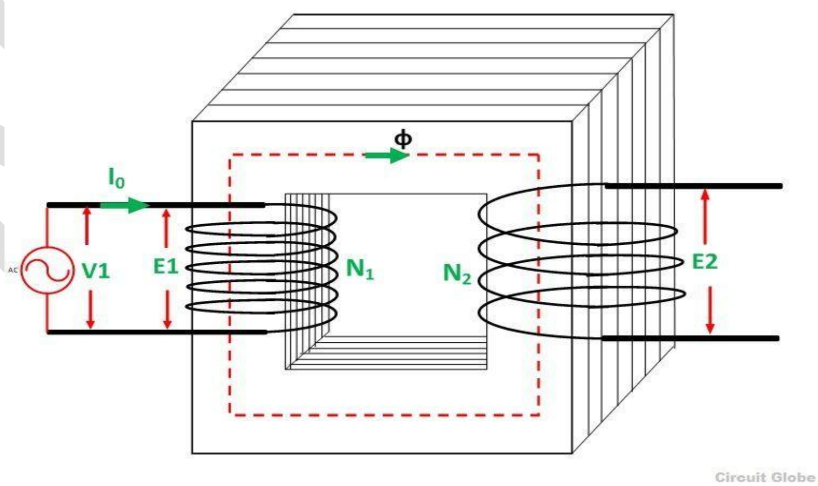
- Source Voltage $V_1 = V_{1'} + r_1I_e + jI_eX_1$, phasor sum. Thus the complete phasor diagram of transformer at no load will be as shown below.



Phasor Diagram of Transformer for Load Condition:

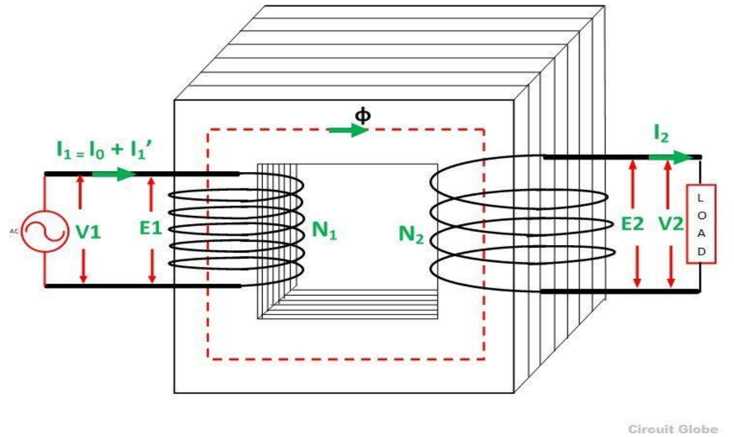
The Operation of the Transformer on Load Condition is explained below:

- 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,

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

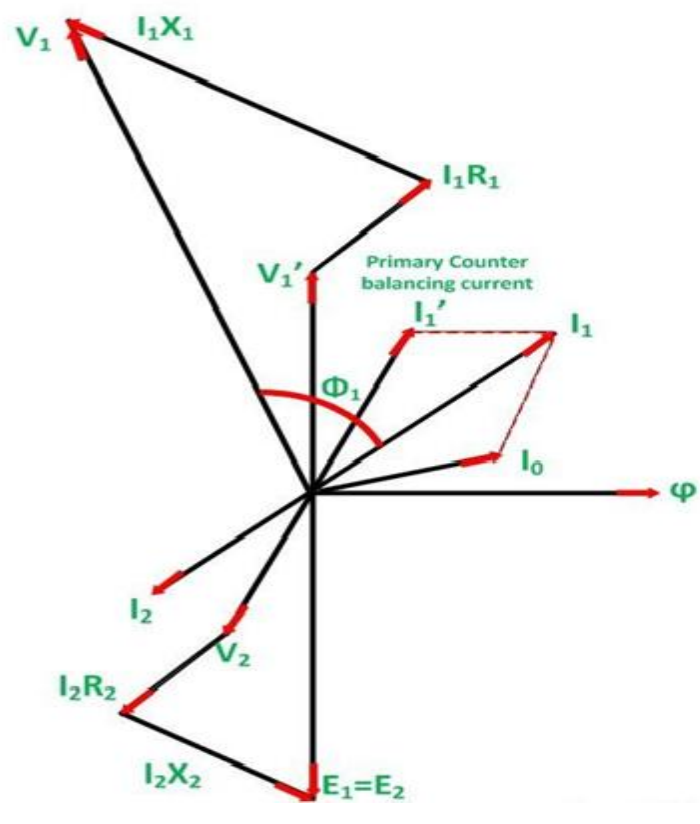
- The phase difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primary side of the transformer.

- 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

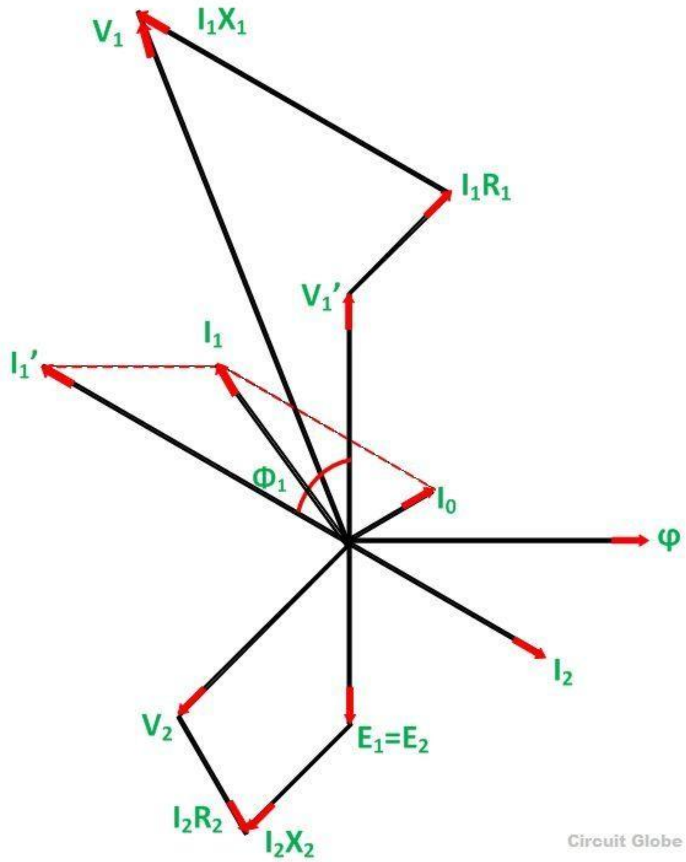
$V_1 = V_1$' + voltage drop

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.

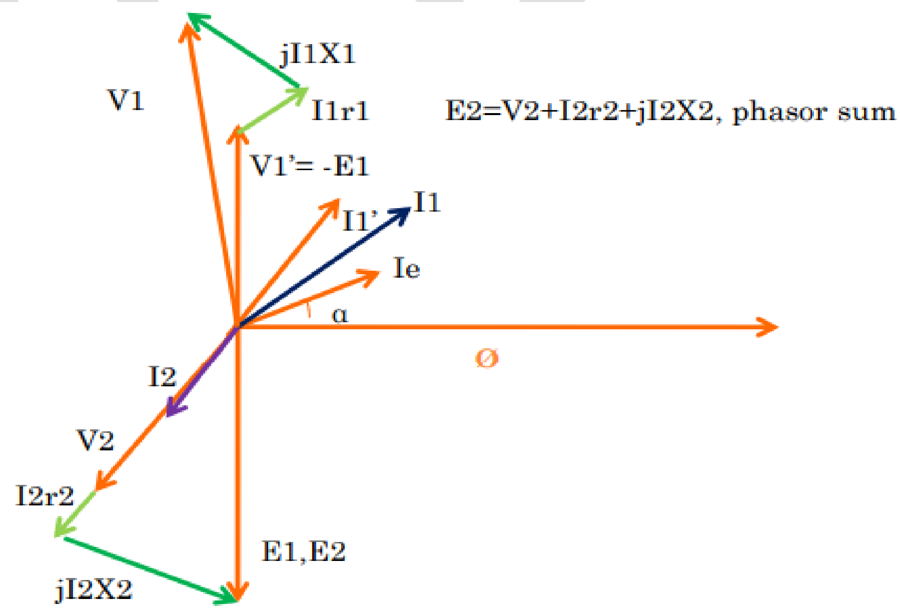
$V_1 = V_1$' + voltage drop

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.

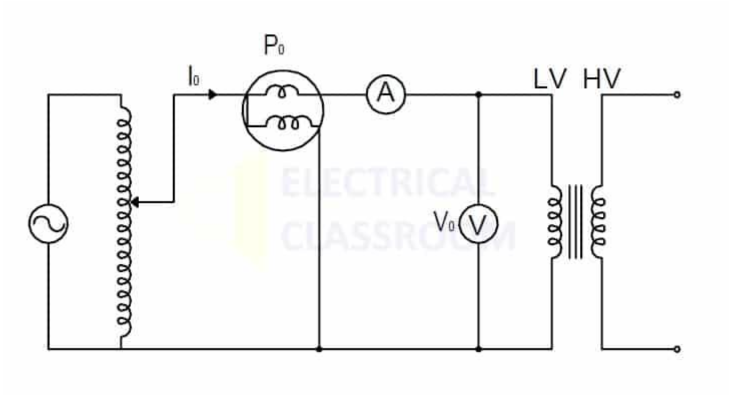
The input voltage, current, and power are measured and based on that the equivalent circuit parameters can be determined.

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.

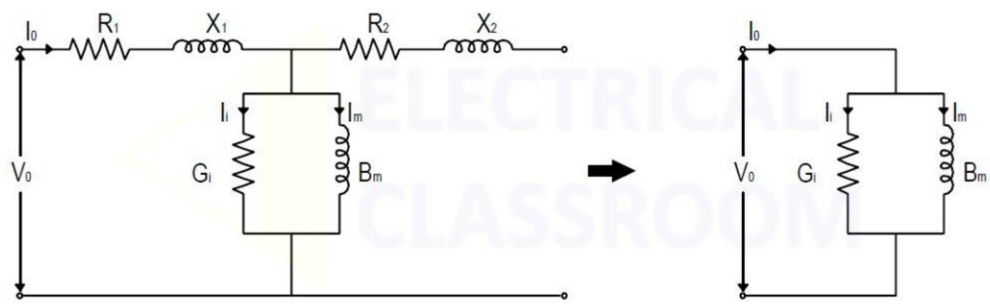


Circuit for open circuit test

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,

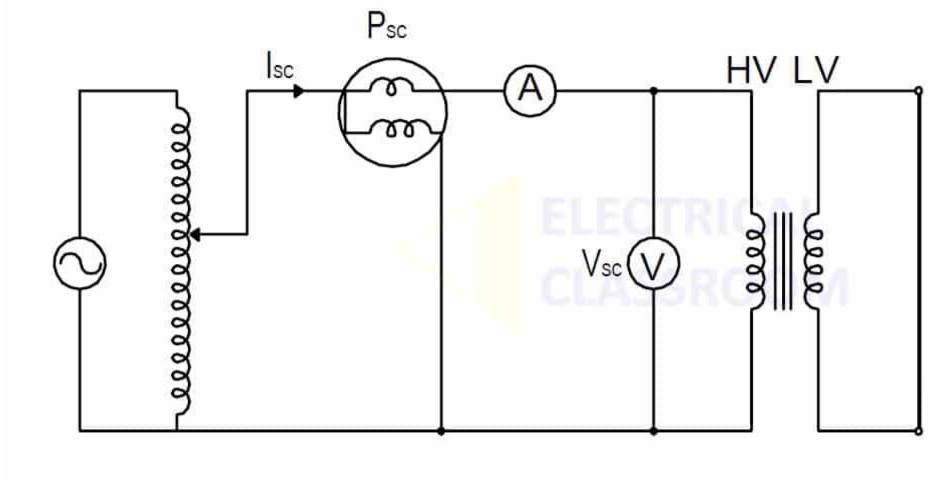
$$B_m = \sqrt{Y_o^2 - G_i^2}$$

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

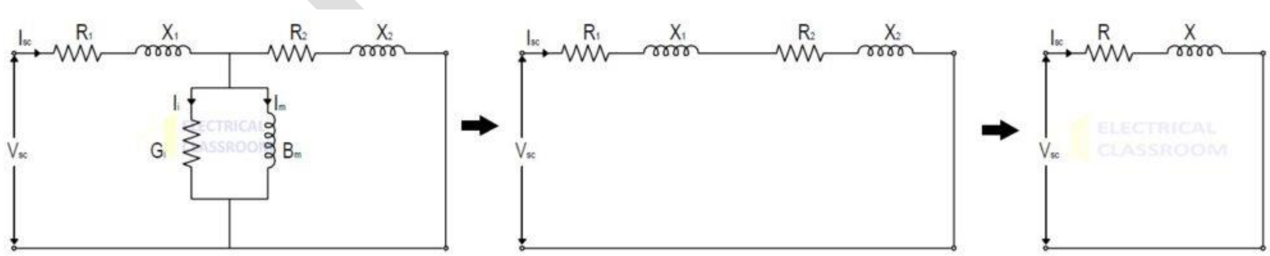


For convenience a variable voltage source is connected to the HV side of the transformer and the LV side of the transformer is short circuited. This is because, the voltage required for short circuit test is typically 5 per cent of the rated value. Since the current rating of HV is less than the LV, 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

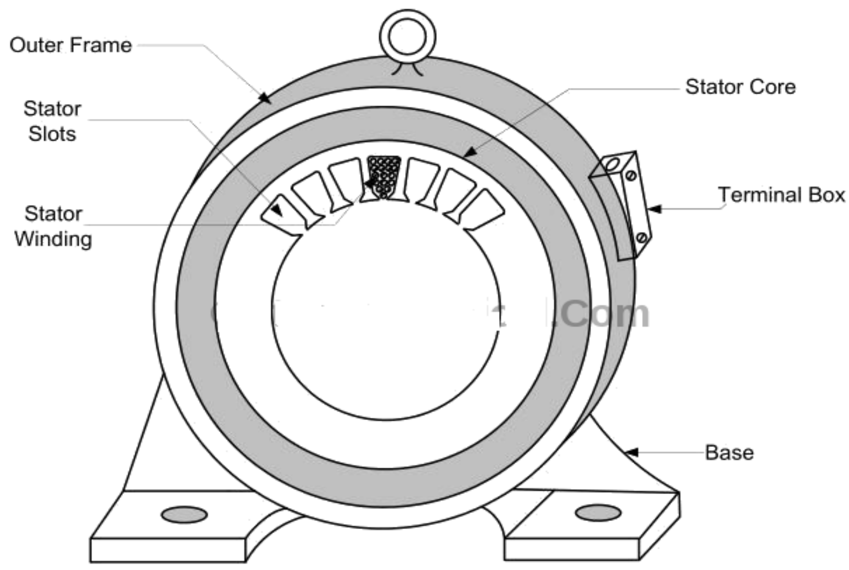
1. **Stator**
2. **Rotor**

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,

$$\mathbf{N_S = 120}\boldsymbol{f}\mathbf{\,/\,P}$$

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.

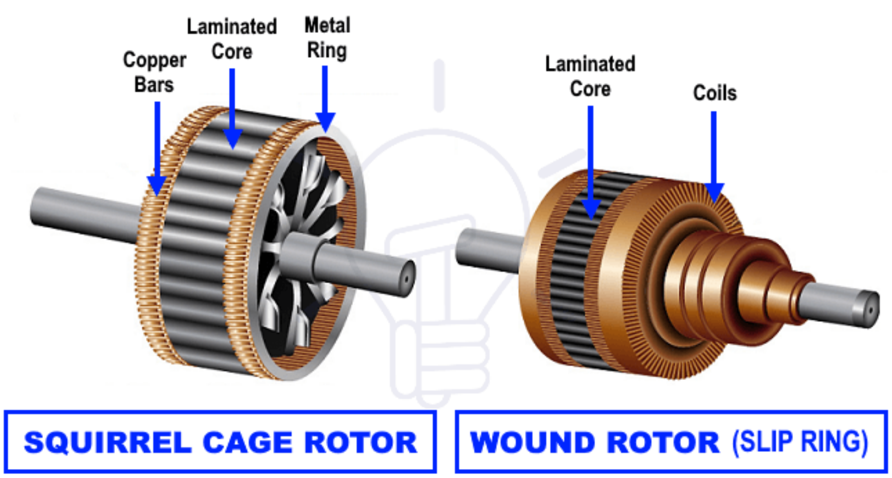
According to the application and type of starting methods of motors, the stator winding is connected in star or delta and it is done by the connection of terminals in the terminal box.

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.

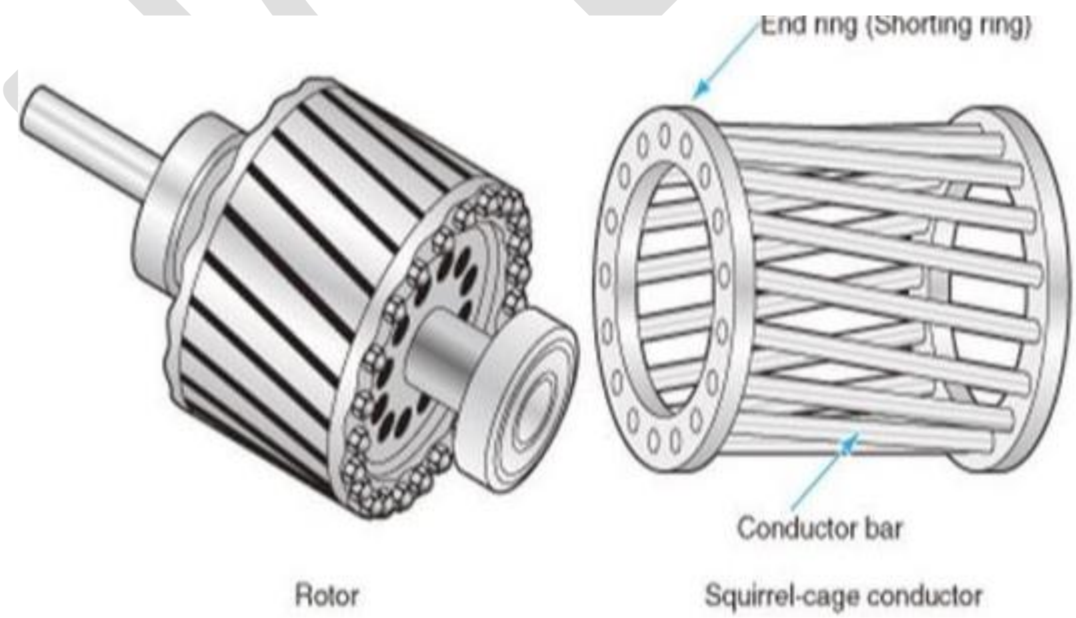
The rotor consists of a cylindrical laminated core and has slots on the outer periphery. The slots are not parallel but it is skewed at some angle. It helps to prevent magnetic locking between the stator and rotor teeth. It results in smooth operation and reduces the humming noise. It increases the length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

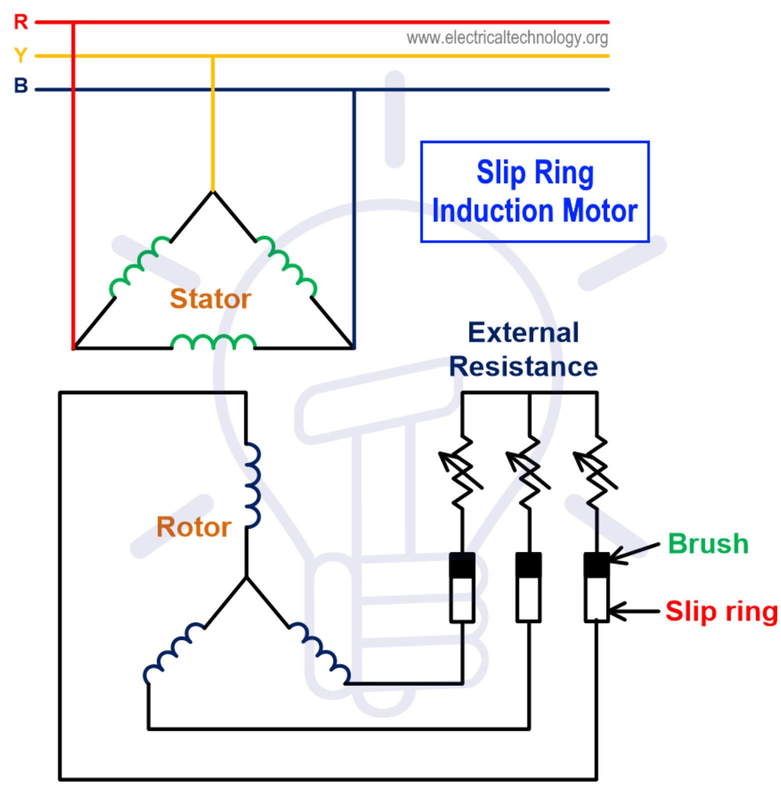
Slip-ring induction motors are also known as wound rotor motor. The rotor consists of a laminated cylindrical core with slots on the outer periphery. The rotor winding is placed inside the slots.

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

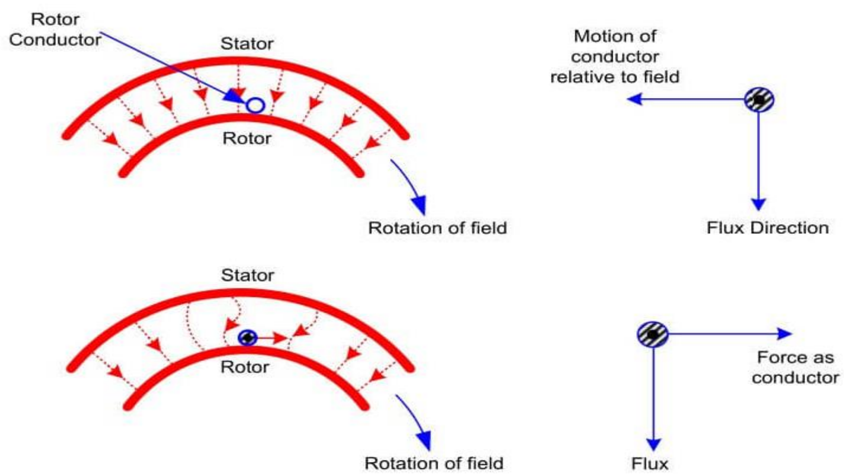
The **slip ring motors** are used in heavy load applications where the high initial torque is needed such as:

- Steel mills
- Lift
- Crane Machine

- Hoist
- Line shafts
- and other heavy mechanical workshops etc

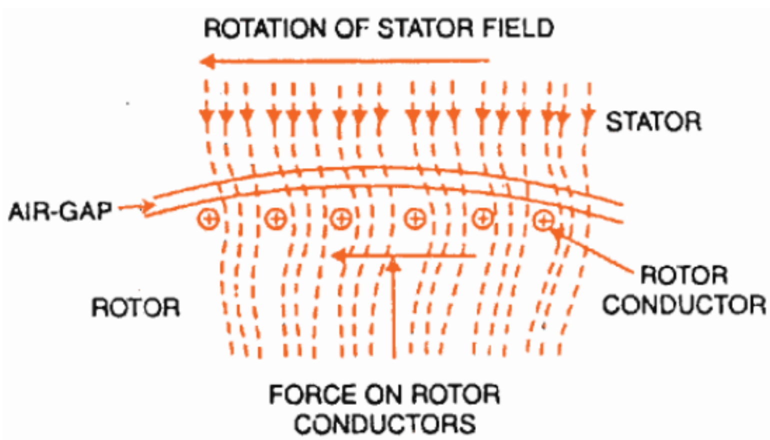
WORKING PRINCIPLE THREE PHASE INDUCTION MOTOR

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**.

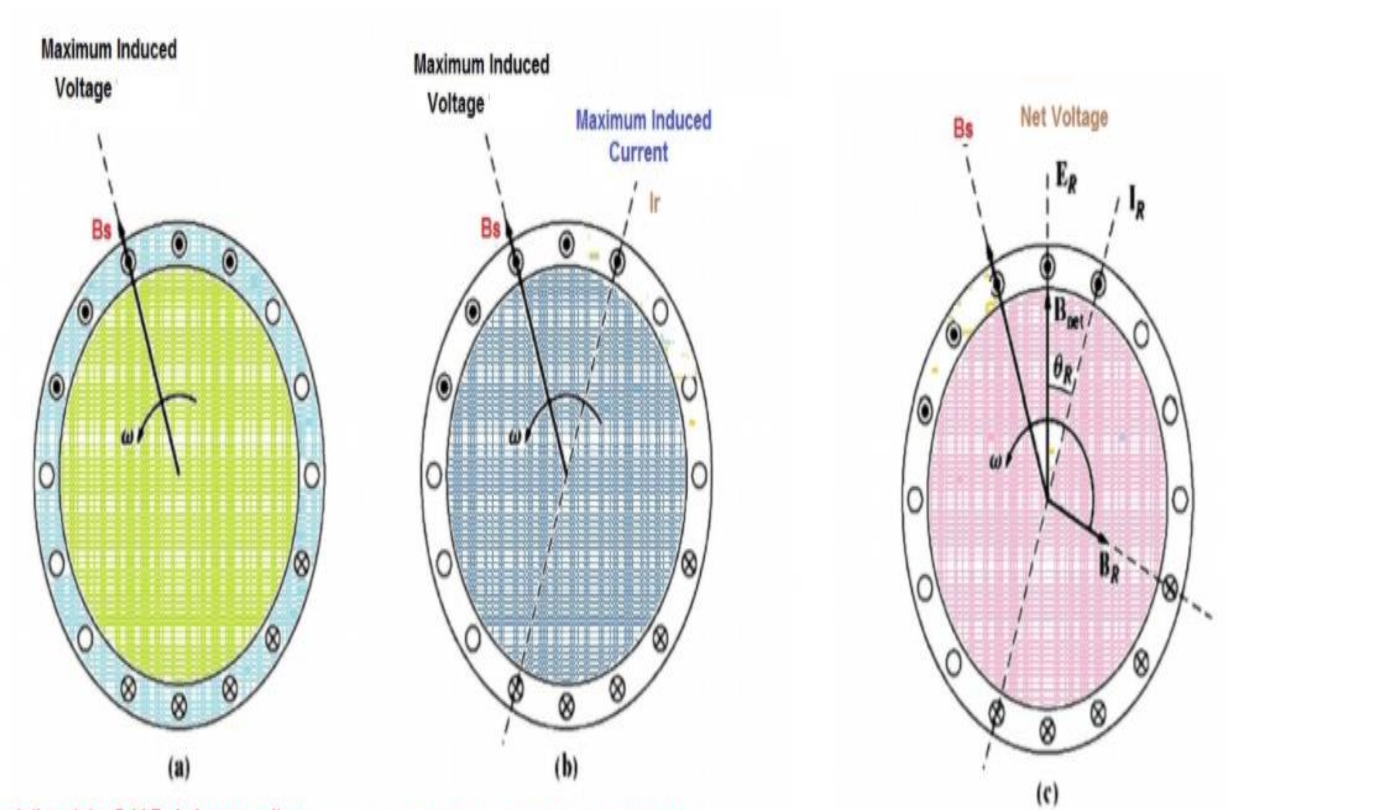
Why the slip is never zero in an induction motor?

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.

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.



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

rotor voltage produces a rotor current flow. which lags behind the voltage because of the inductance of the rotor

the rotor current produces a rotor magnetic field BR lagging 90° behind itself. and BR imeracts 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.

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

- 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.

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

- 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.

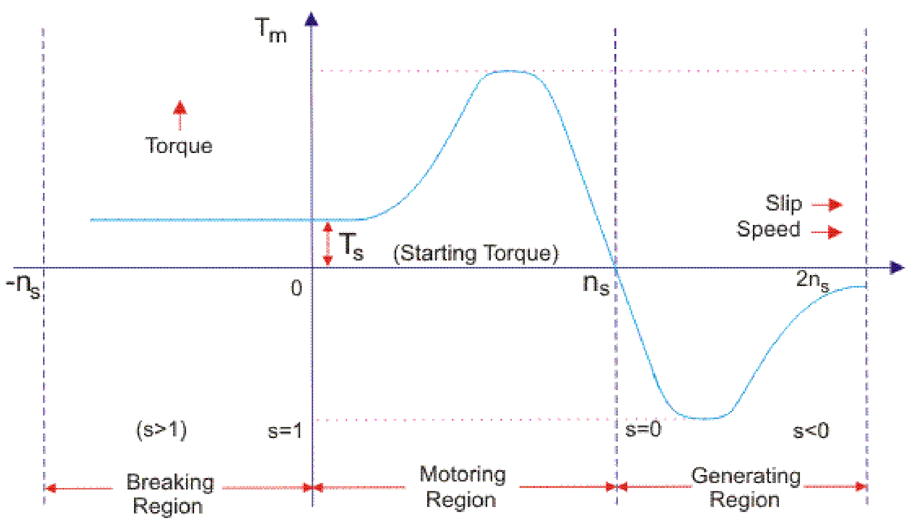
$$T_{ind} = kB_R \times Bs$$

- 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

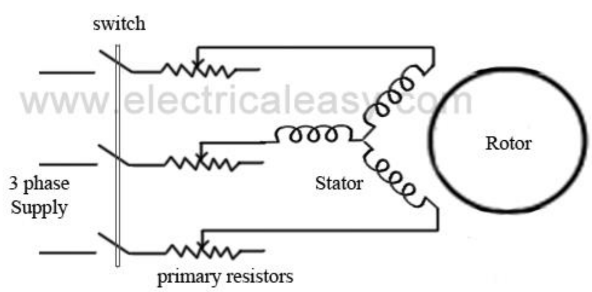
Small three phase induction motors can be started direct-on-line, which means that the rated supply is directly applied to the motor. But, as mentioned above, here, the starting current would be very large, usually 5 to 7 times the rated current. The starting torque is likely to be 1.5 to 2.5 times the 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

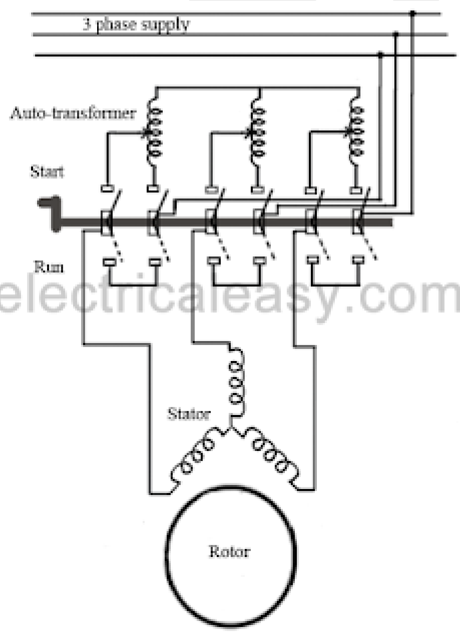
1. Using Primary Resistors:



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:



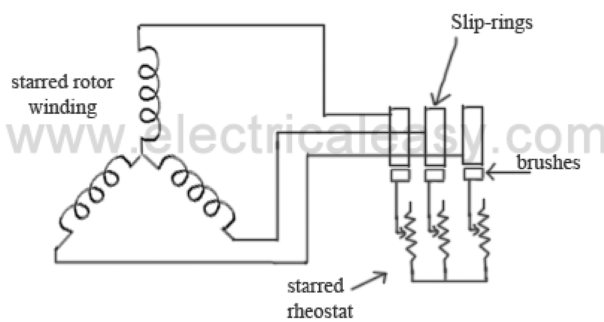
Auto-transformers are also known as auto-starters. They can be used for both star connected or delta connected squirrel cage motors. It is basically a three phase step down transformer with different taps provided that permit the user to start the motor at, say, 50%, 65% or 80% of line voltage. With 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.*

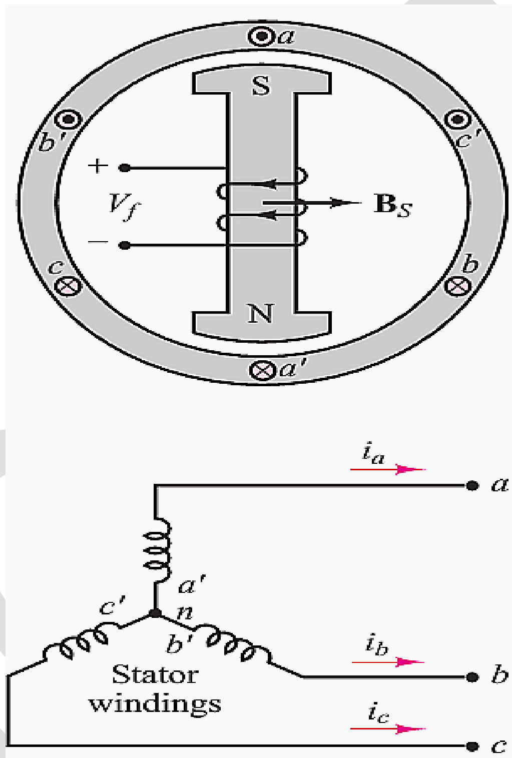


Figure – Two-pole three-phase stator

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.

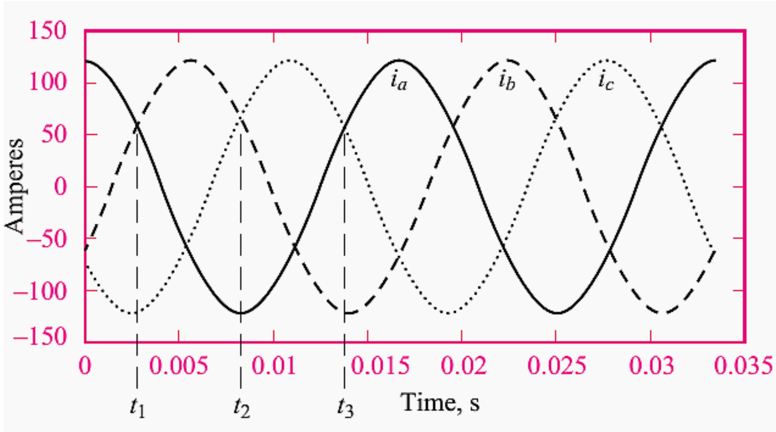


Figure – Three-phase stator winding currents

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.

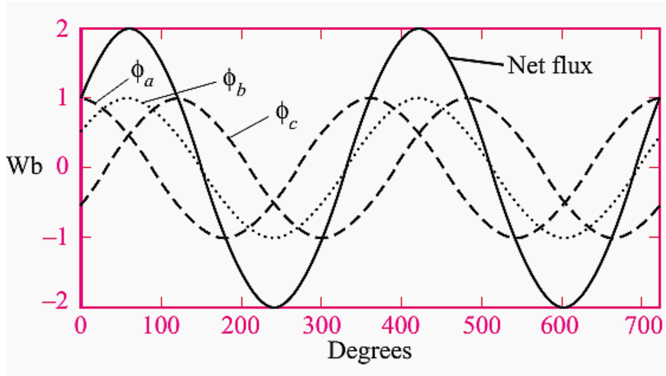


Figure – Flux distribution in a three-phase stator winding as a function of angle of rotation

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.

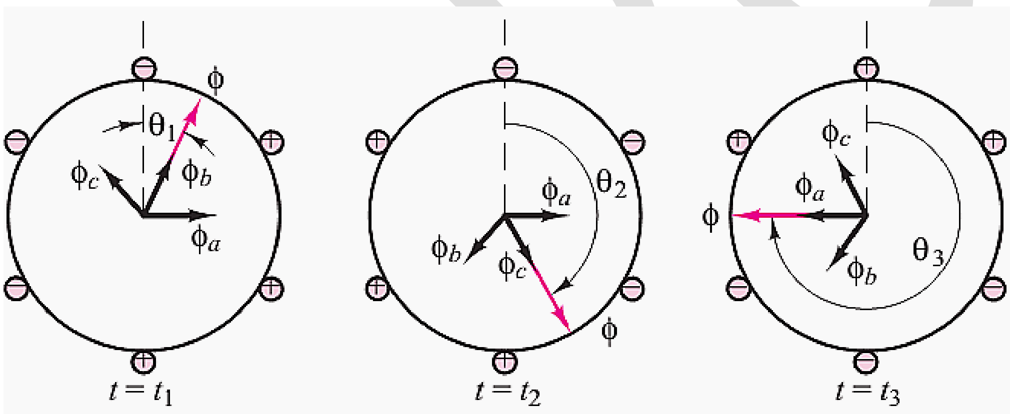


Figure – Rotating flux in a three-phase machine

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.*

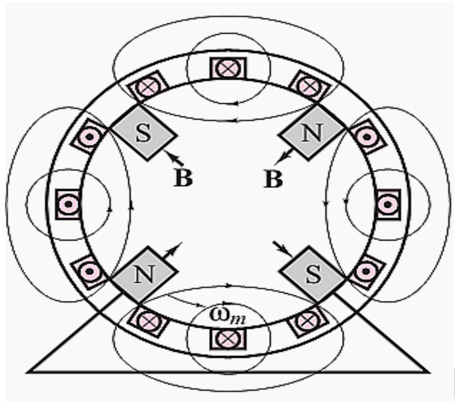


Figure – Four-pole stator

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** $\boldsymbol{\gamma}$ 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 III

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 $\Phi_m/2$.

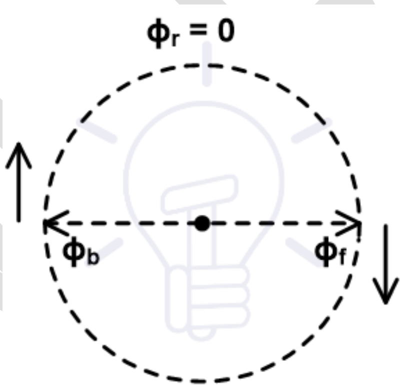
Out of these two fields, one field Φ_f is rotating in an anticlockwise direction and the second field Φ_b is rotating in a clockwise direction. Therefore, the resultant field is zero.

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

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

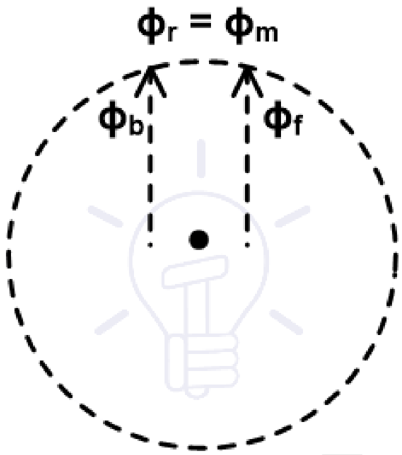
$$\mathbf{\Phi_r = 0}$$

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

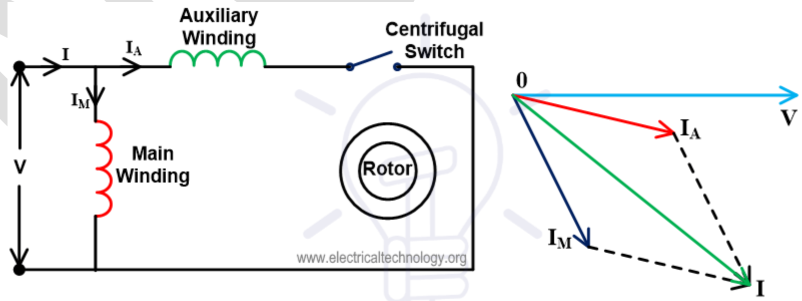
SPLIT PHASE INDUCTION MOTOR

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

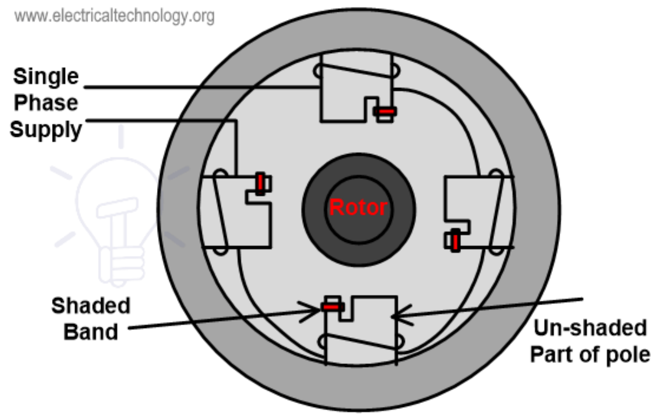
As compared to other types of single-phase induction motor, this motor has a different construction and working principle. This type of motor does not require auxiliary winding.

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.

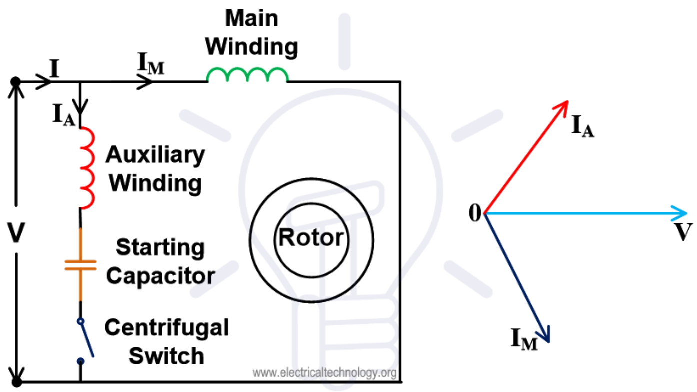
The shaded ring is a highly inductive coil. So, it will oppose the main flux when both fluxes are in the same direction and it will increase the main flux when both fluxes are in the opposite direction.

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.

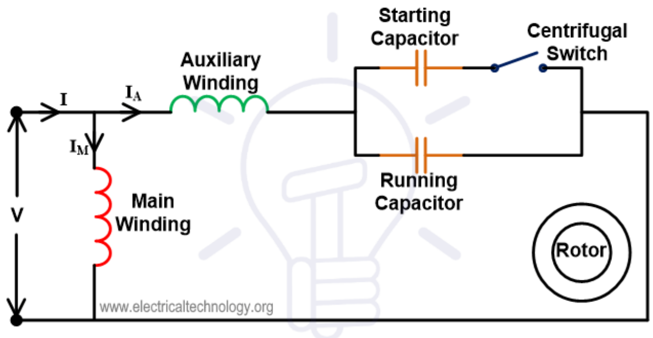
So, the starting torque of this motor is very high compared to the split-phase induction motor. The starting torque of this motor is 300% more than the full load torque.

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.

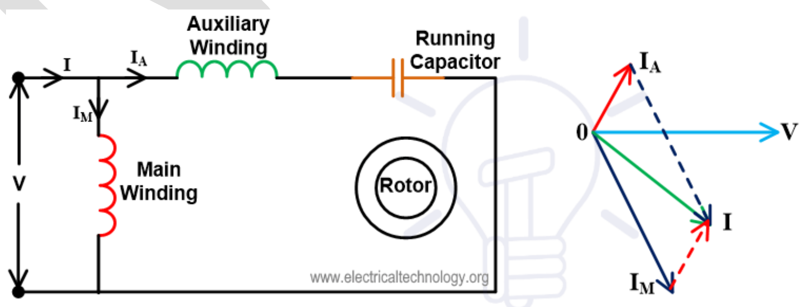
Therefore, this can be used in the application where high starting torque is required like a refrigerator, air conditioner, ceiling fan, compressor, etc.

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.

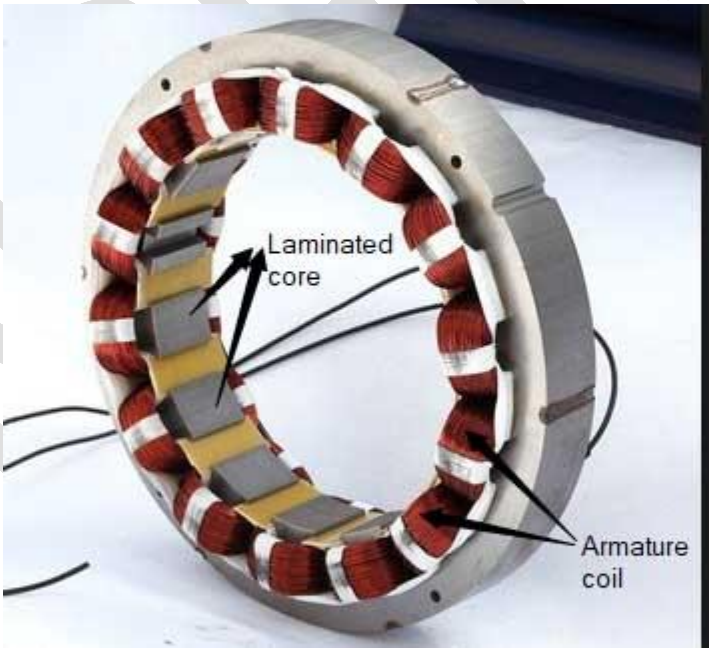
ALTERNATORS

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

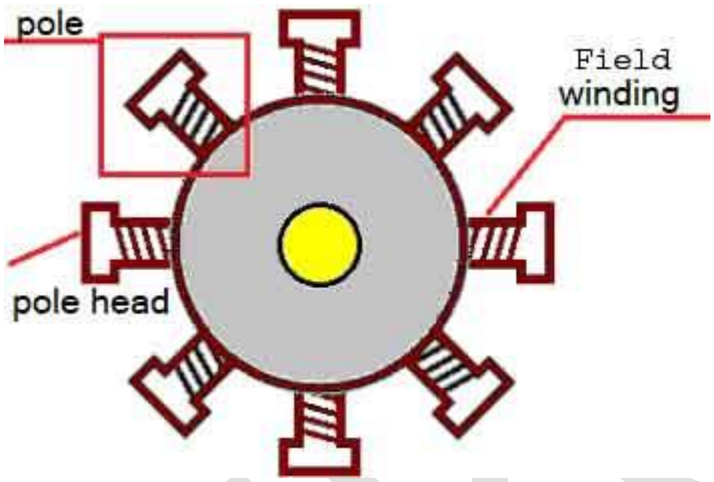
- The revolving field structure of the electrical machine is called as the rotor. In a synchronous generator, the rotor carries a field winding which is supplied by the DC source.
- The DC source is also called an exciter which is generally a small d.c shunt or compounded generator mounted on the shaft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

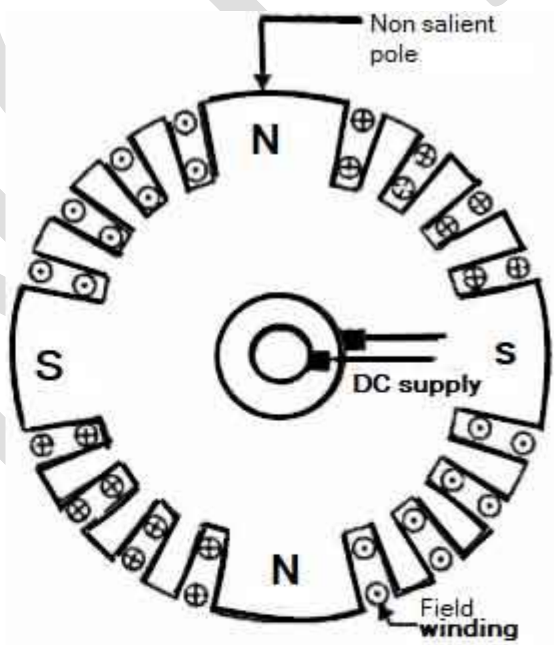
Disadvantage of Salient Pole Rotor

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

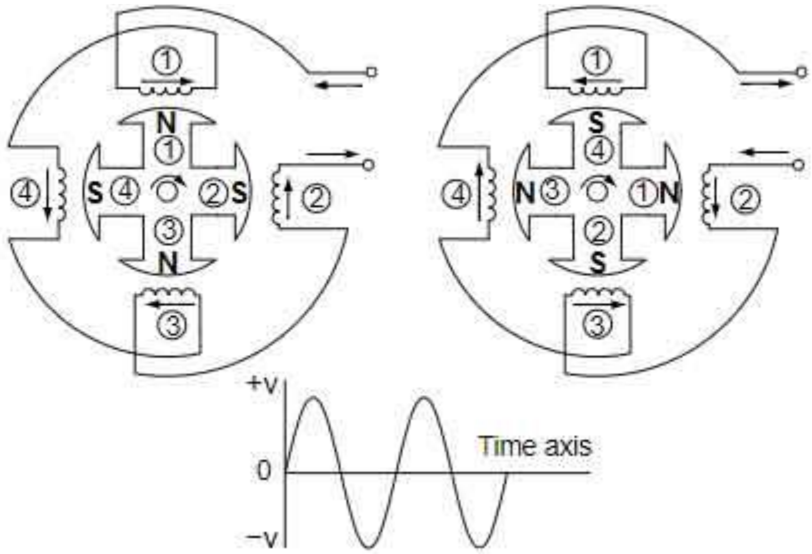
The alternator can be divided into different types based on their application, prime mover, design, output power, and cooling.

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.

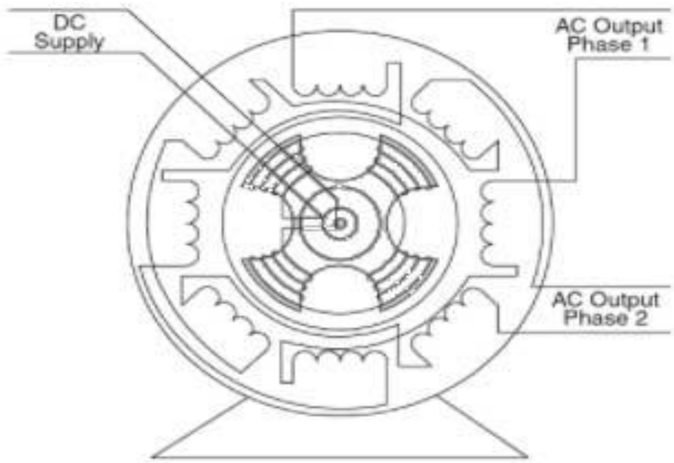


Single phase Alternator

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.

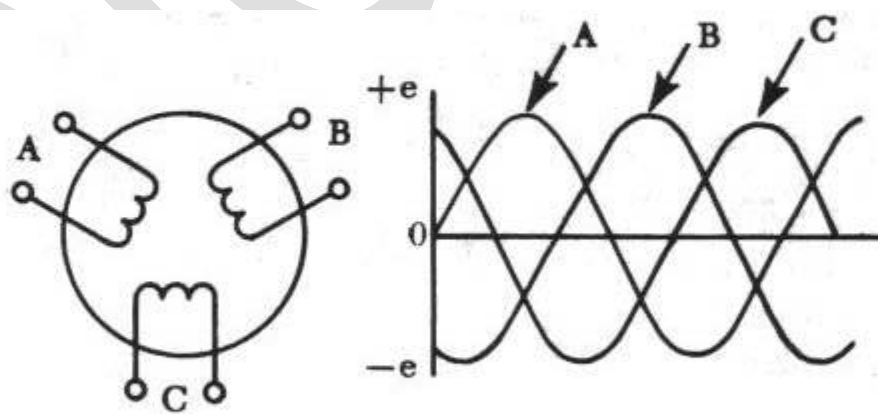
TWO-PHASE ALTERNATOR



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

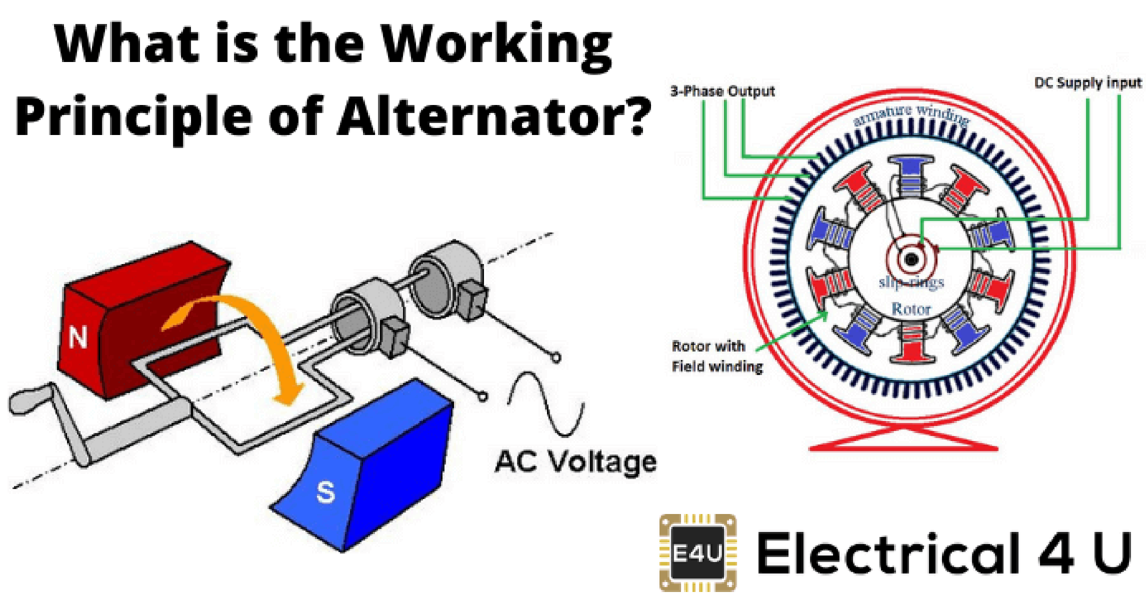
Alternator based on their Prime-mover

- Turbo Generator
- Hydro Generator
- Diseal Engine driven Alternator

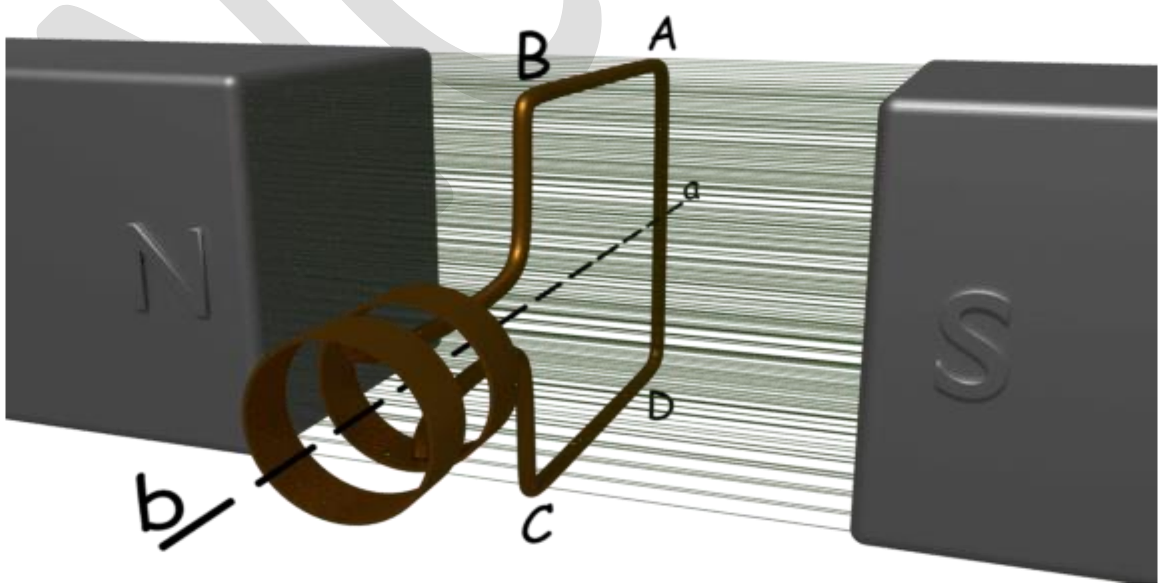
Alternator Based on Type of their Design

- Salient pole Rotor
- Smooth cylindrical Rotor

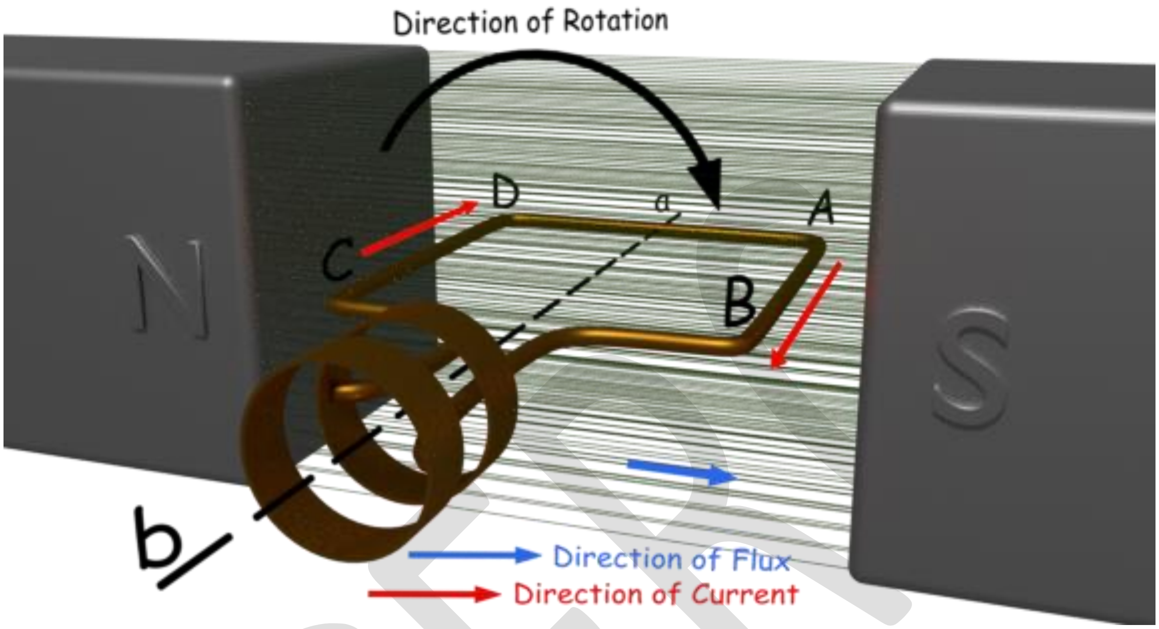
WORKING PRINCIPLE OF ALTERNATORS



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.



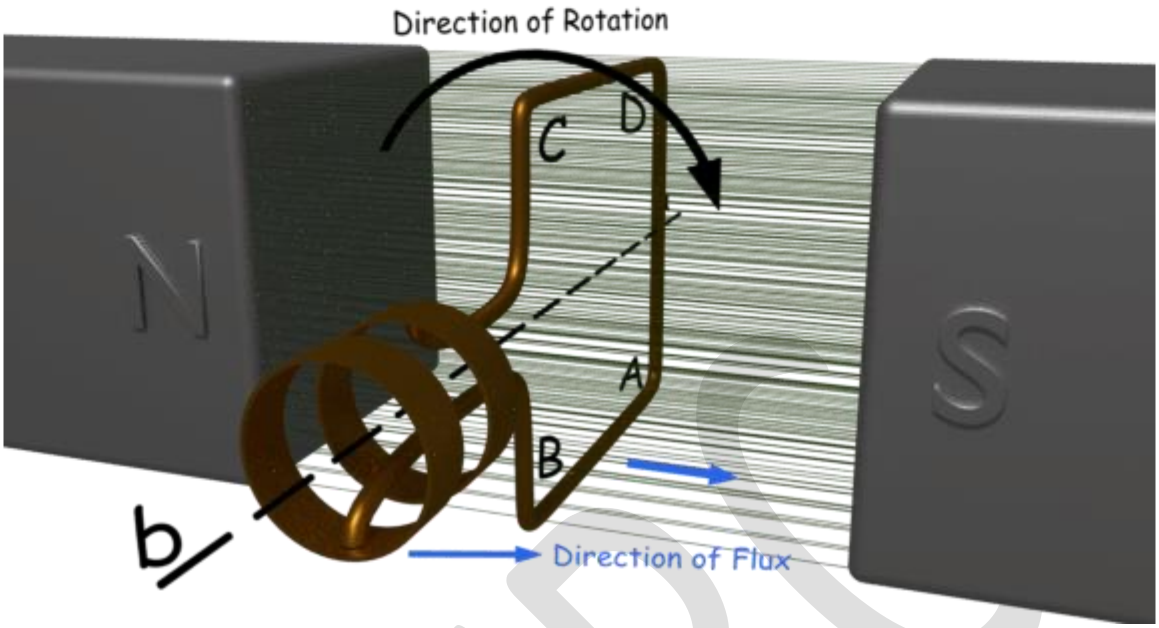
For understanding **working of alternator** let us think about a single rectangular turn placed in between two opposite magnetic poles as shown above.



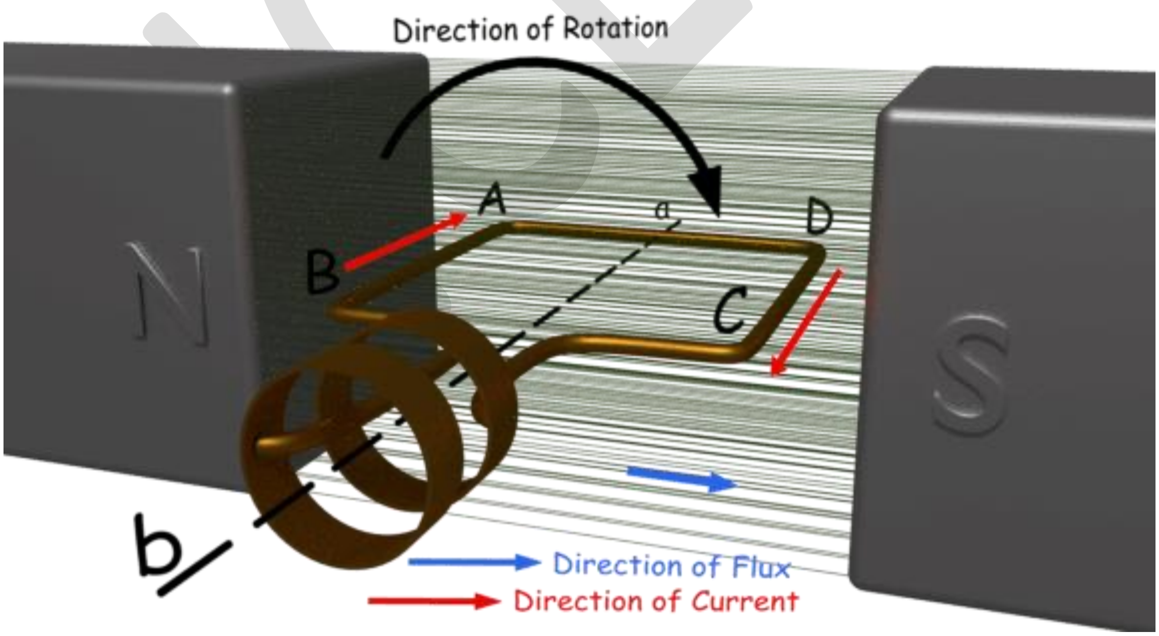
Say this single turn loop ABCD can rotate against axis a-b. Suppose this loop starts rotating clockwise. After 90^o rotation the side AB or conductor AB of the loop comes in front of S-pole and conductor CD comes in front of N-pole. At this position the tangential motion of the conductor AB is just perpendicular 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.



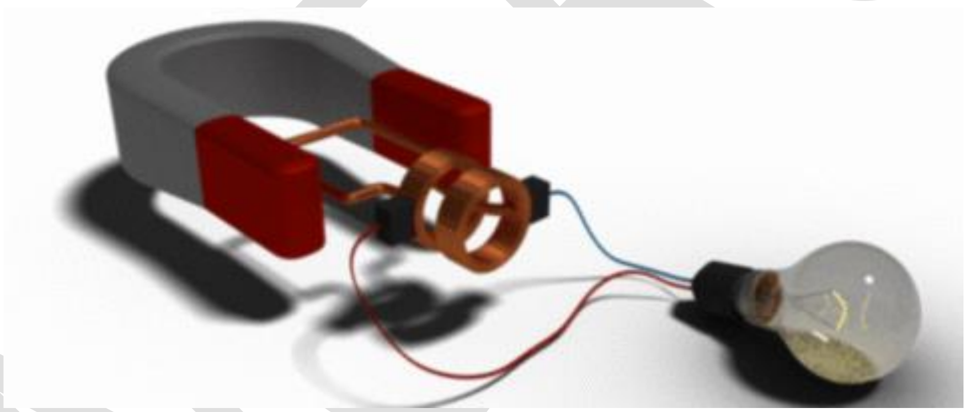
After another clockwise rotation of 90° the turn again comes to horizontal position, and here conductor AB comes under N-pole and CD comes under S-pole, and here if we again apply Fleming right-hand rule, we will see that induced current in conductor AB, is from point B to A and induced current in the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

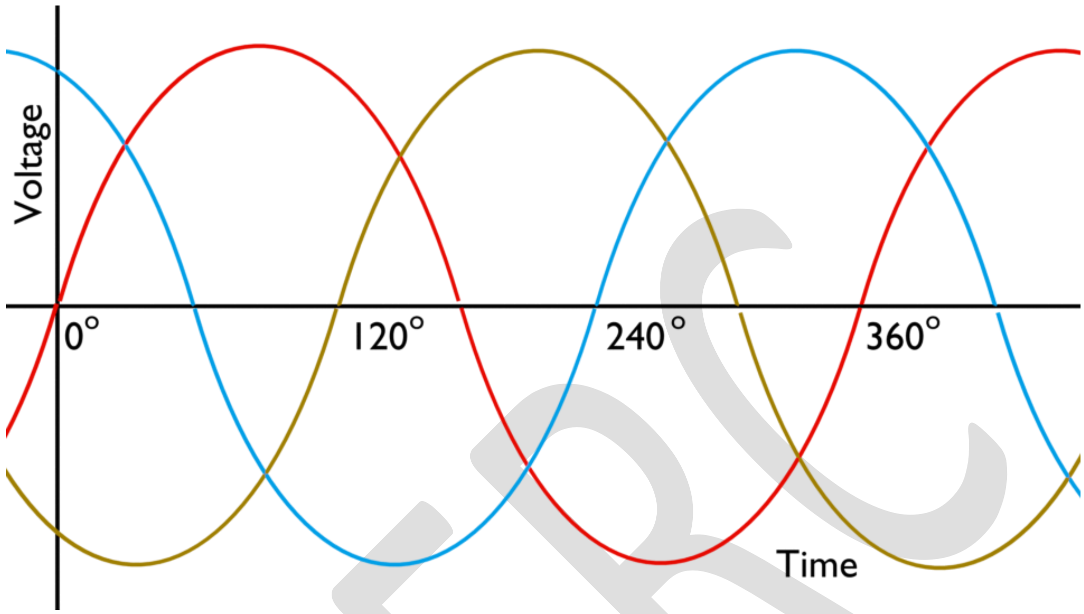
While the turn further proceeds to its vertical position the current is again reduced to zero. So if the turn continues to rotate the current in turn continually alternate its direction. During every full revolution of the turn, the current in turn gradually reaches to its maximum value then reduces 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° 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,

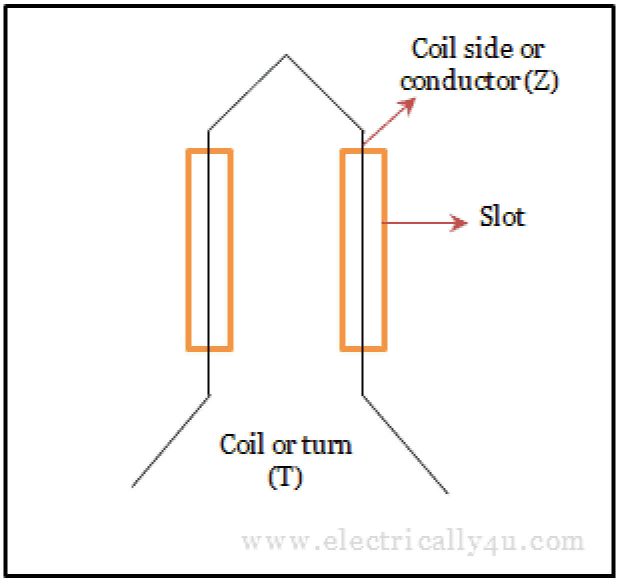
K_f = Form factor

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,

$$Average\ emf\ induced\ per\ conductor\ =\ 2\Phi f Z\ =\ 4\Phi f T\ \ volts$$

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

$$where,\ K_d\ =\ \frac{\sin\ {}^{m\beta}/_2}{m\ \sin\ {}^{\beta}/_2}$$

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

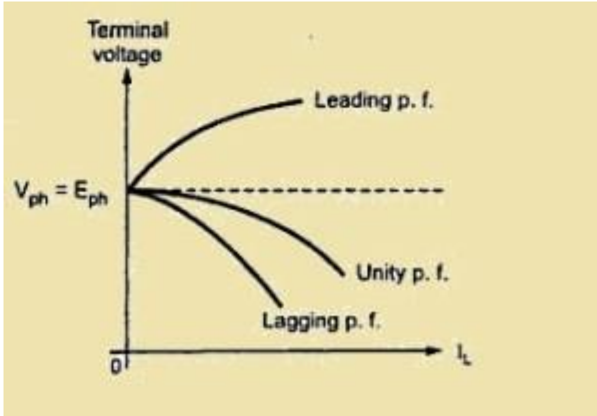
E_{ph}= 4.44 x 1 x 0.96 x 0.02 x 50 x 240 = 1022.97 V

$$E_L = \sqrt{3}\, E_{ph} = \sqrt{3}\ x\ 1022.97 = 1771.83\ V$$

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)

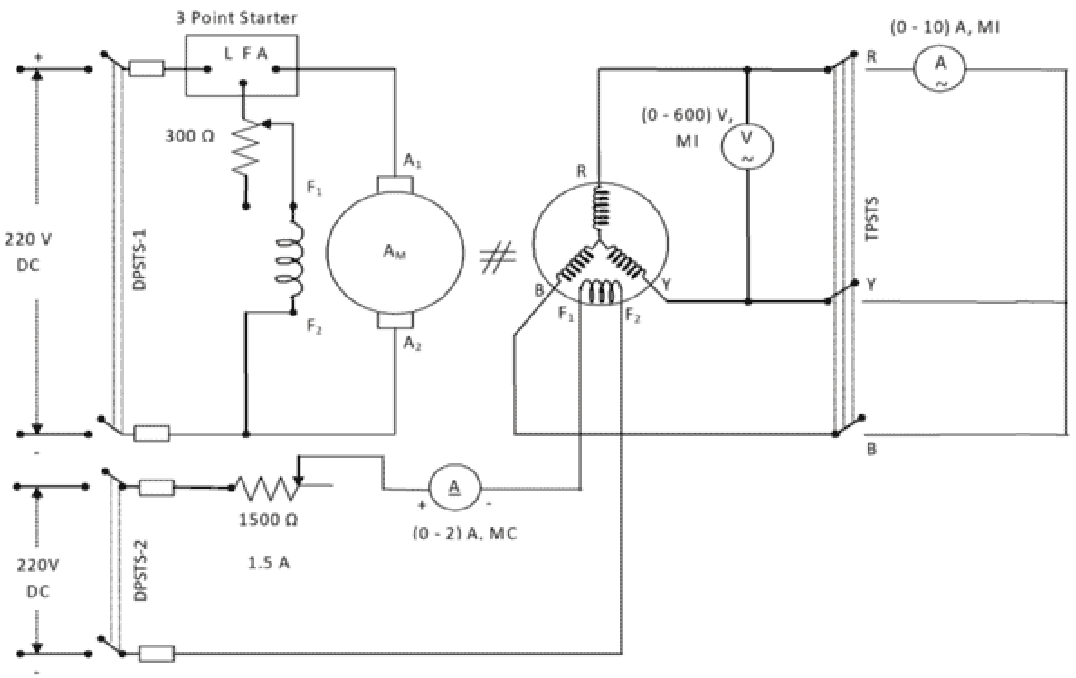
Armature Resistance per phase

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.

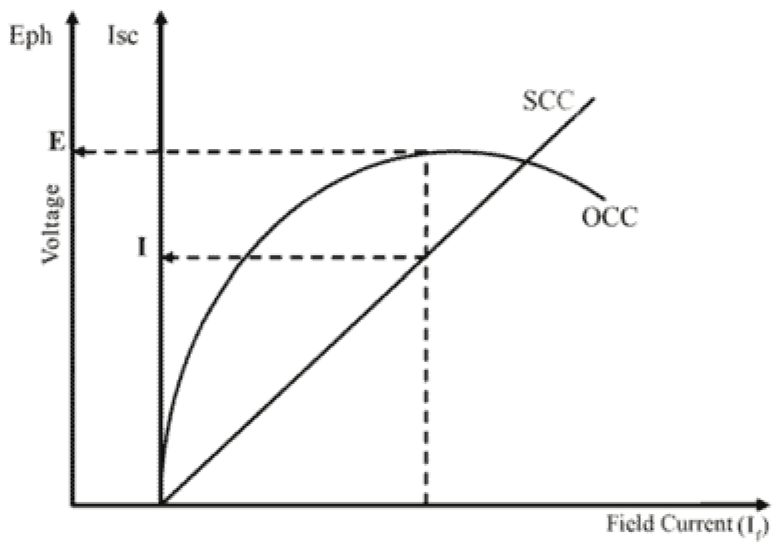


Experiment to determine the voltage regulation by EMF method

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,

$$Voltage\ Regulation = \frac{E_{ph} - V_{ph}}{V_{ph}}$$

MODULE 4

SPECIAL ELECTRICAL MACHINES

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.

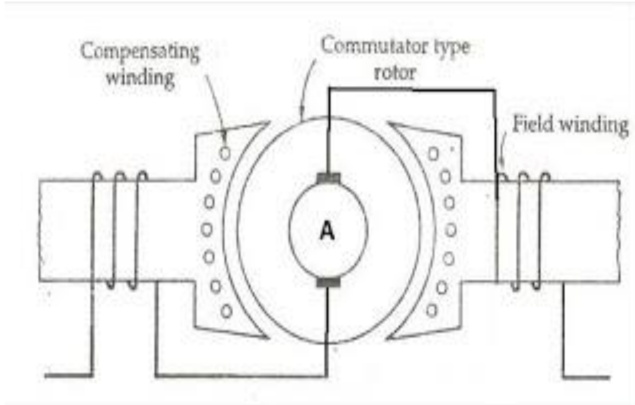
This motor is a commutator type motor.

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.

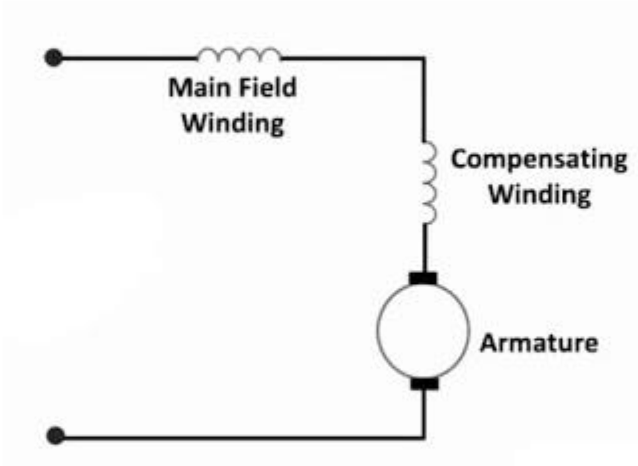
The armature is wound type same as small dc motor, it has laminated core having straight or skewed slots and commutator to which armature winding leads are connected.

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.

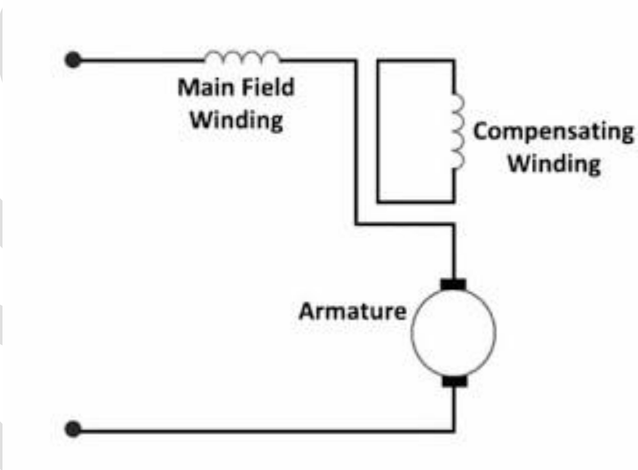
In compensated type motor, compensating winding is used to reduced reactance voltage drop in armature when it operated on AC supply. This voltage is caused by the transformer action due to alternating flux.

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.

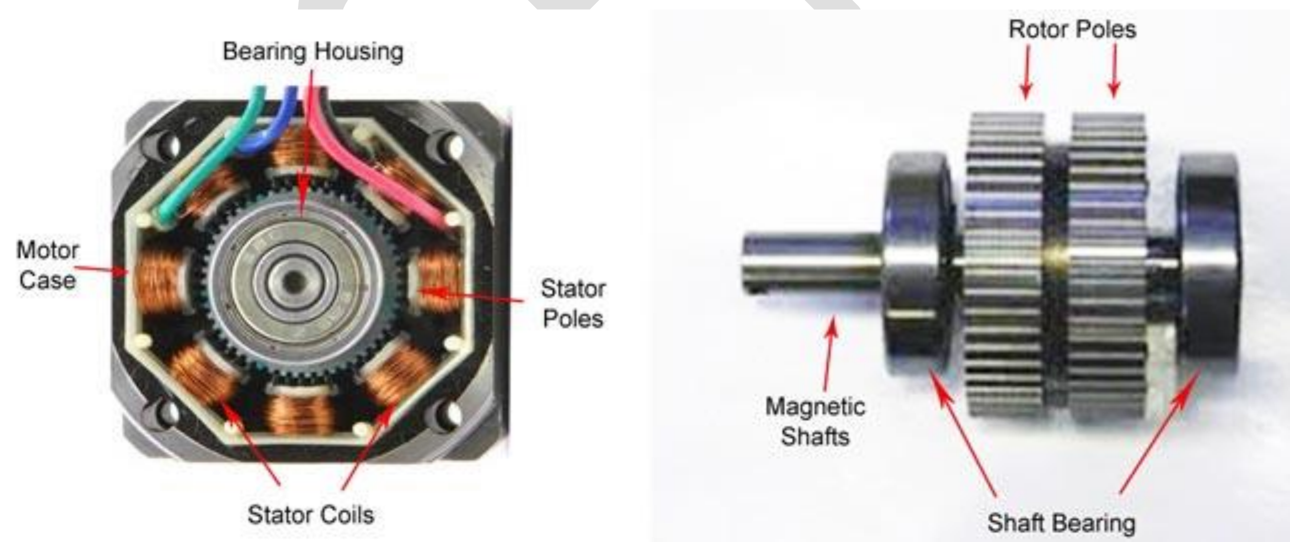


Fig. 2: General Overview Of Internal Structure And Working Of Typical Stepper Motor

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.

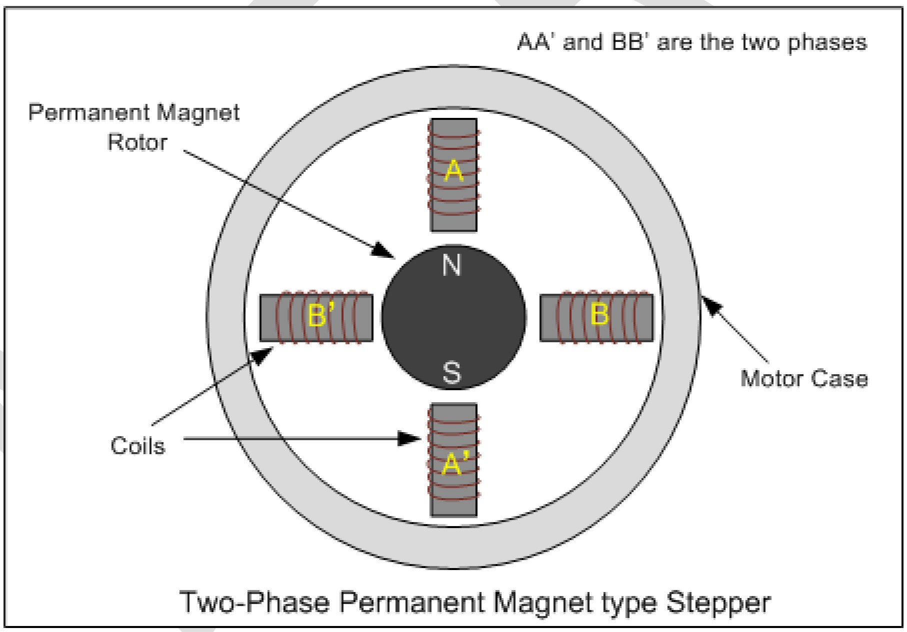


Fig. 3: Crossectional Diagram Of Two Phase Permanent Stepper Motor

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.

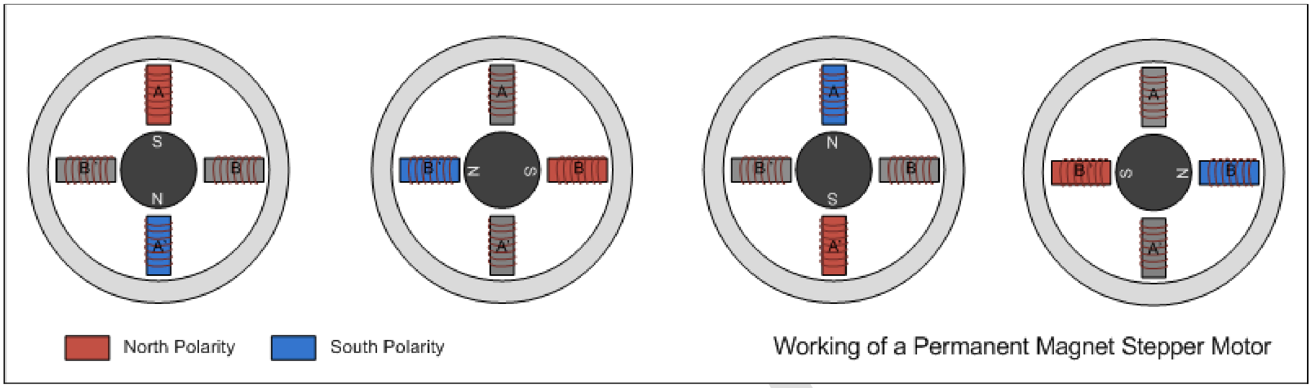


Fig. 4: Diagram Explaining Working Of Permanent Magnet Stepper Motor

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

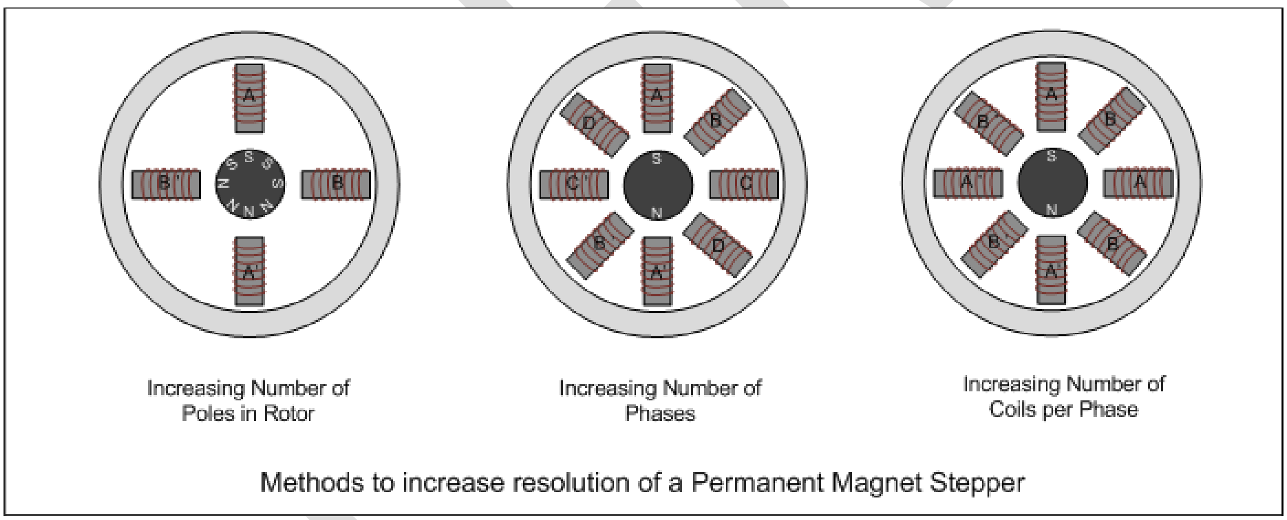


Fig. 5: Figure Showing Ways To Increase Resolution Of Permanent Magnet Stepper Motor

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.

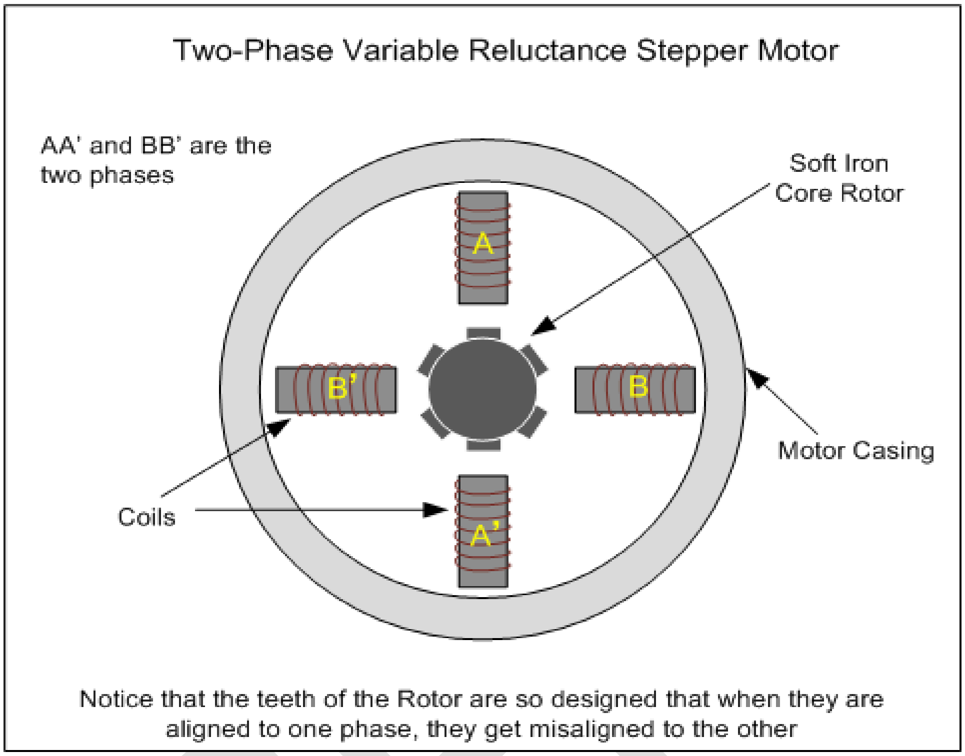


Fig. 6: Basic Diagram Of Two-Phase Variable Reluctance Stepper Motor

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.

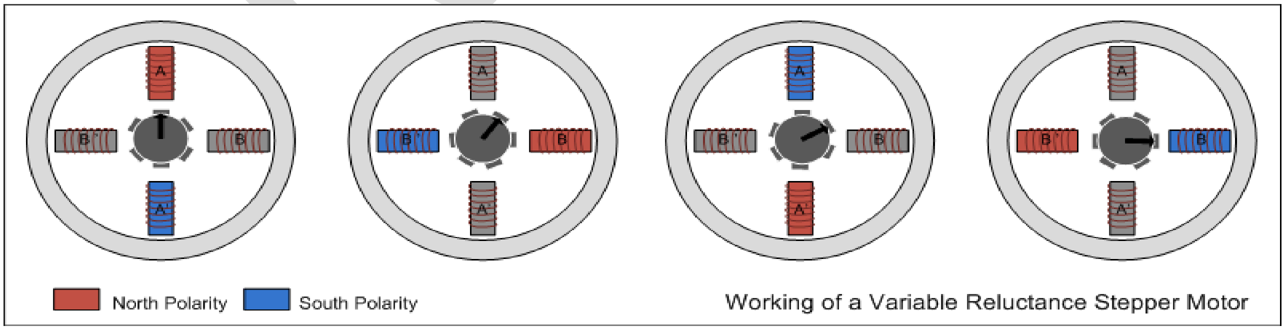


Fig. 7: Diagram Explaining Working Of Variable Reluctance Stepper

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.

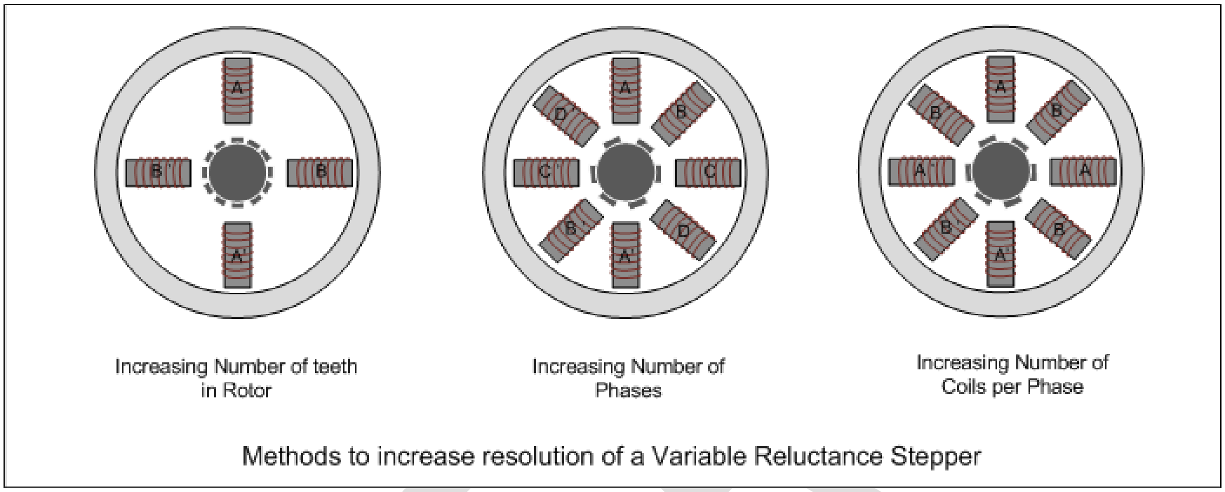


Fig. 8: Figure Showing Ways To Increase Resolution Of Variable Reluctance Stepper Motor

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.

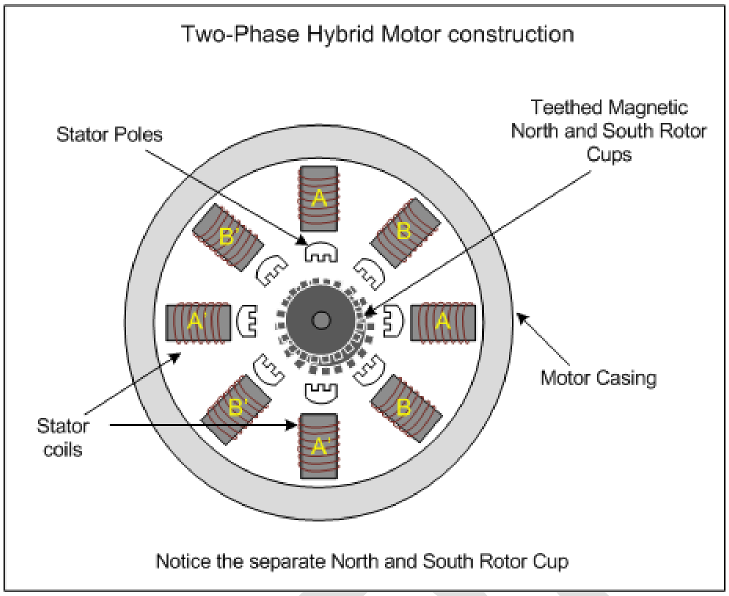


Fig. 9: Construction Of Two phase Hybrid Motor

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.

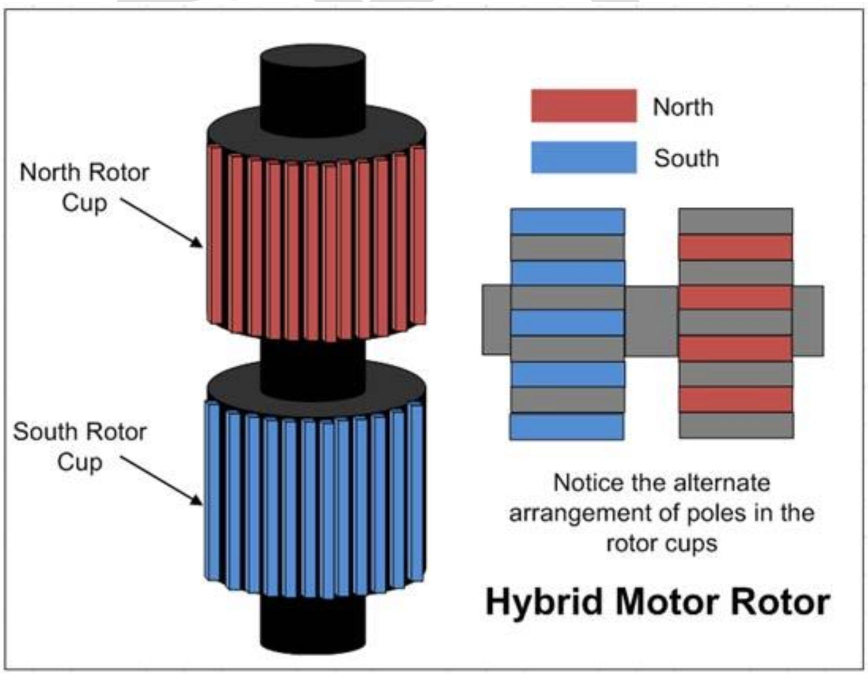


Fig. 10: Diagram Showing Internal Structure Of Magnetic Rotor In Hybrid Motor

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

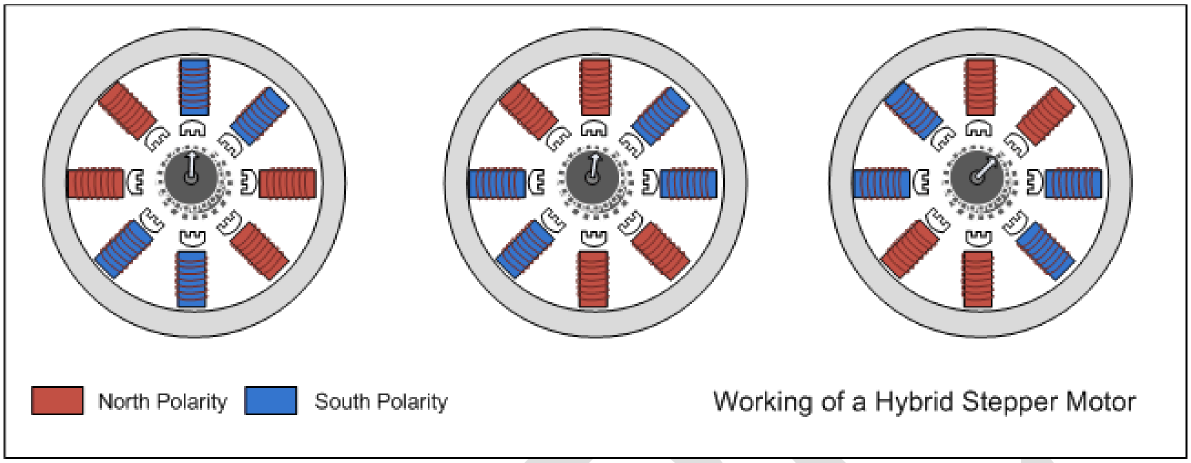


Fig. 11: Diagram Explaining Working Of Hybrid Stepper Motor

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.

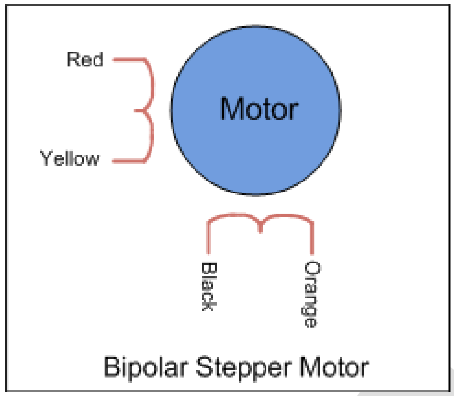


Fig. 14: Wave Drive Stepping Mode Pattern In Stepper Motor

2. Full Drive :

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

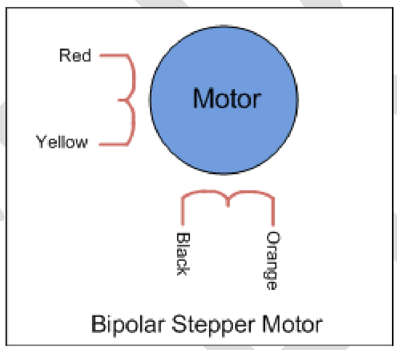


Fig. 15:Full Drive Stepping Mode pattern In Stepper Motor

3. Half Drive :

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

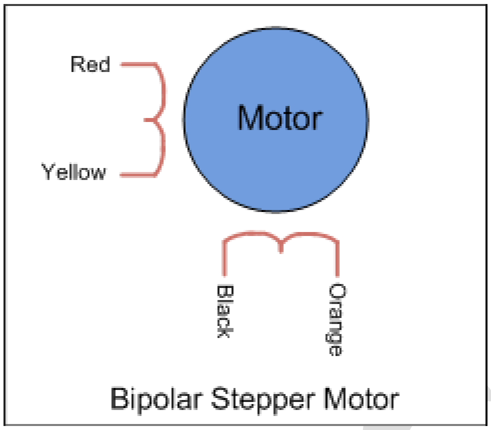


Fig. 16: Half Drive Stepping Mode Pattern In Stepper Motor

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**

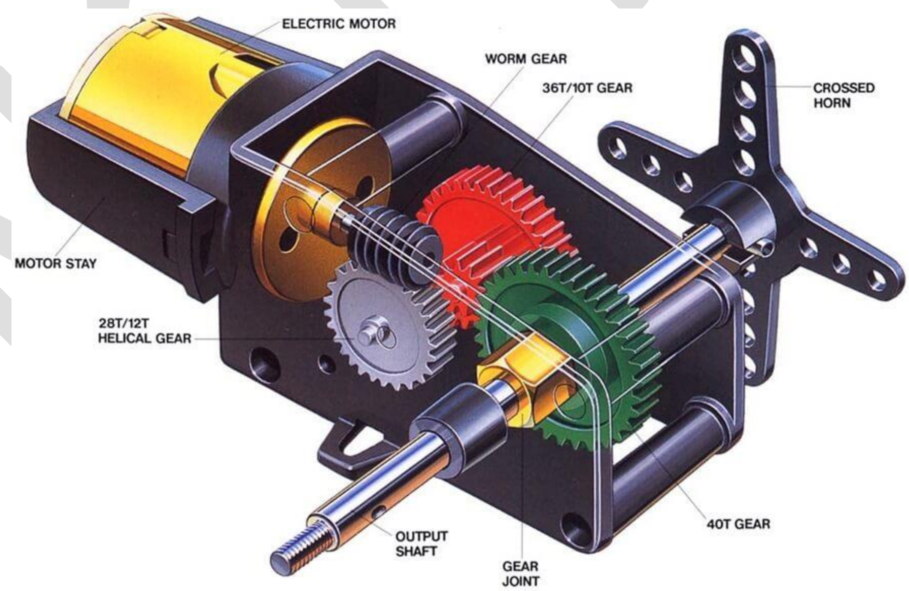
AC servo motor is powered with an AC source while DC servo motor is powered with a DC source. AC servo motor has less efficiency, operates smoothly, delivers low power, small weight, and low maintenance is required. Whereas, DC servo motor has high efficiency, delivers high power, large weight, and requires 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.

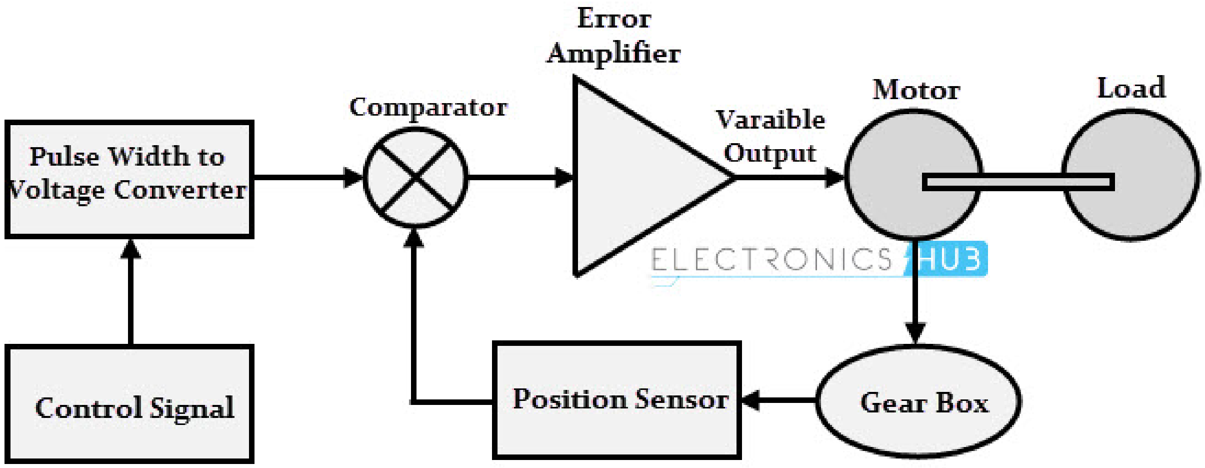
The Servo motor is DC motor or AC Motors which has 5 following parts:-

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.

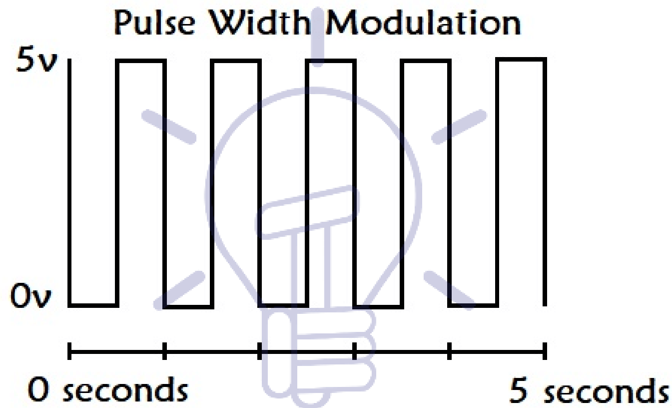
In AC servomotors we have two parts rotor and stator. A stator has two windings reference winding and controlled winding which are displaced by 90 degrees. Fixed signal is applied at reference winding while a variable error signal is applied at the controlled winding.

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.

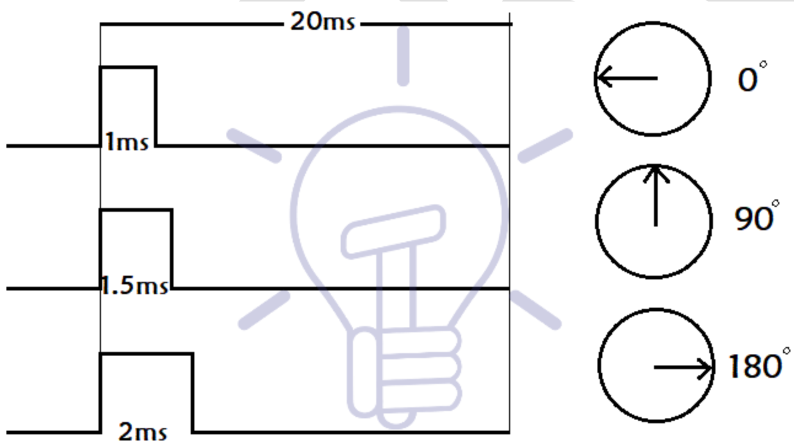
Controlling of Servo Motor:

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.

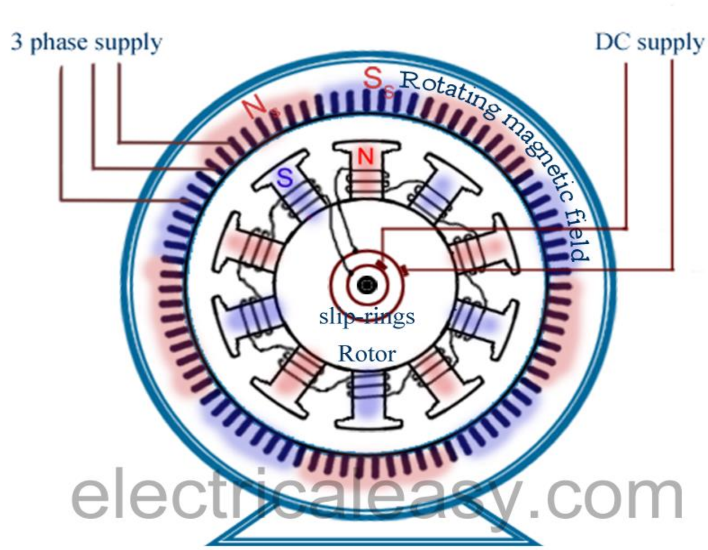
Disadvantages:

- 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

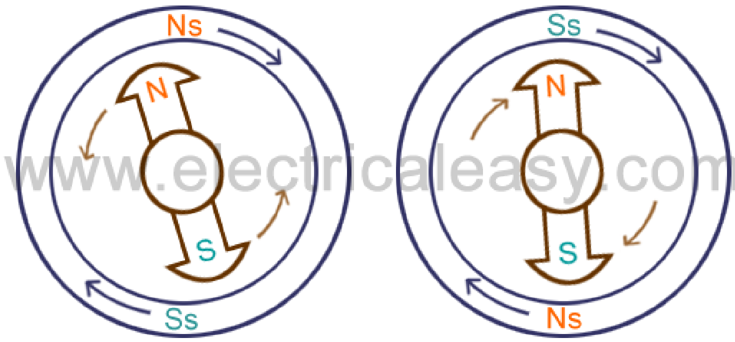


The **construction of a synchronous motor** (with salient pole rotor) is as shown in the figure at left. Just like any other motor, it consists of a stator and a rotor. The stator core is constructed with thin silicon lamination and insulated by a surface coating, to minimize the eddy current and hysteresis 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.

INTRODUCTION TO POWER ELECTRONICS

INTRODUCTION

he study of controlling the flow of electrical energy with the help of electronic circuits is defined as Power Electronics.

The subject of Power Electronics is the merger of the field of electrical power system and solid state electronic devices. It is the discipline that involves the study, analysis, and design of circuits that convert electrical energy from one form to another.

What is the difference between the linear Electronics and Power Electronics?

The specifications in linear Electronics are Gain and Bandwidth. Whereas the specifications in Power Electronics are Efficiency and Distortion.

Study of Power Electronics involves (but not limited to)

- Power Semiconductor Devices – Construction, Characteristics, Operation, protection (Just remember that there is huge difference between signal level semiconductor devices and Power semiconductor devices. Power semiconductor devices have to handle high voltage and current. In order to withstand the high voltage/current ratings, power devices construction is different from the construction of their low power counterparts)
- Energy storage elements
- Various Power Converter Topologies
- Control Strategies, Drive circuits of Topologies
- EMI, EMC, Heat Dissipation techniques

Applications of Power Electronics:

We can realise the applications of Power Electronics everywhere in our day-to-day life (home, office, factory, car, hospital, theatre etc.)

Some of the typical applications are

- Domestic and theatre lighting
- Industrial Process in the chemical, paper and steel industries
- Motor drives from food mixers, washing machines through to lifts and locomotives
- Power supplies for laboratories and uninterruptible power for vital loads
- Generation and transmission control

Industrial Applications:

- Industrial applications mainly consist of two areas, motor control and power supplies. The motors which are controlled vary from very large(used in steel mills) to smaller ones(used in machine tools). Power supplies for battery charging, induction heating, electroplating and welding.

Consumer Applications:

- Consumer applications cover many different areas in the home, such as audio amplifiers, heat controls, light dimmers, security systems, motor control for food mixers and hand power tools.

Transportation Applications:

- Transportation applications like motor drives for electric vehicles, locomotives. In addition to this non-motor drive applications like traffic signal control, vehicle electronic ignition and vehicle voltage regulation.

Aerospace Applications:

- Aerospace and defence applications include VLF transmitters, power supplies for space and aircraft; and switching using solid state relays and contactors.

SILICON CONTROLLED RECTIFIER(SCR)

We know that the diode allows electric current in one direction and blocks electric current in another direction. In other words, the diode converts the AC current in to DC current. This unique behavior of the diodes makes it possible to build different types of rectifiers such as half wave, full wave and bridge rectifiers. These rectifiers converts the Alternating Current into Direct Current.

The half wave, full wave, and bridge rectifiers uses normal p-n junction diodes (two layer diodes). So if the voltage applied to these diodes is high enough, then the diodes may get destroyed. So the rectifiers cannot operate at high voltages.

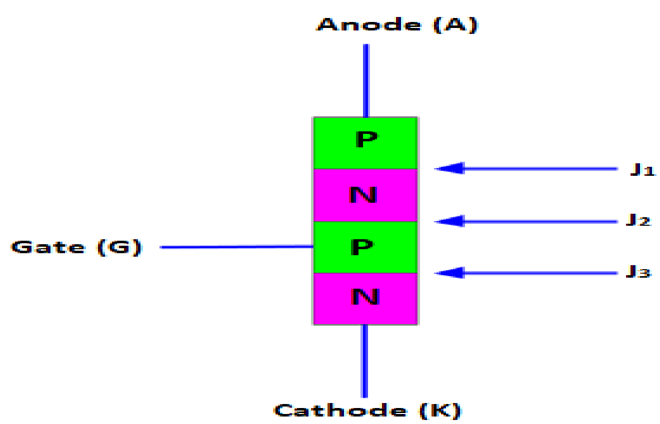
To overcome these drawback, scientists have developed a special type of rectifier known as Silicon Controlled Rectifier. These rectifiers can withstand at high voltages.

Silicon Controlled Rectifier Definition

A Silicon Controlled Rectifier is a 3 terminal and 4 layer semiconductor current controlling device. It is mainly used in the devices for the control of high power. Silicon controlled rectifier is also sometimes referred to as SCR diode, 4-layer diode, 4-layer device, or Thyristor. It is made up of a silicon material which controls high power and converts high AC current into DC current (rectification). Hence, it is named as silicon controlled rectifier.

What is Silicon Controlled Rectifier?

Silicon controlled rectifier is a unidirectional current controlling device. Just like a normal p-n junction diode, it allows electric current in only one direction and blocks electric current in another direction. A normal p-n junction diode is made of two semiconductor layers namely P-type and N-type. However, a SCR diode is made of 4 semiconductor layers of alternating P and N type materials.



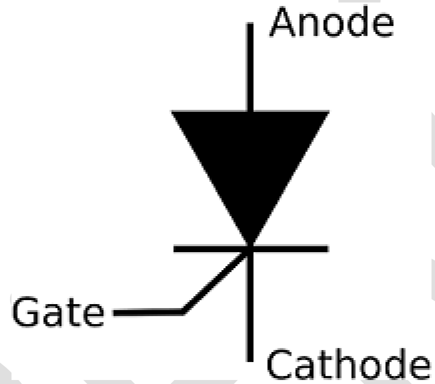
SCR Structure

The principle of p-n-p-n switching was developed by Tanenbaum, Goldey, Moll and Holonyak of Bell Laboratories in 1956. The silicon controlled rectifier was developed by a team of power engineers led by Gordon Hall and commercialized by Frank W. Frank W. "Bill" Gutzwiller in 1957. In the early days of this device development, it is often referred by names like SCR and controlled rectifier. However, now-a-days, this device is often referred by Thyristor.

Silicon controlled rectifiers are used in power control applications such as power delivered to electric motors, relay controls or induction heating elements where the power delivered has to be controlled.

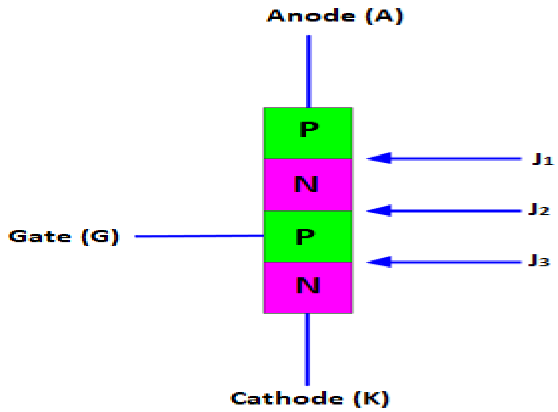
Silicon Controlled Rectifier Symbol

The schematic symbol of a silicon controlled rectifier is shown in the below figure. A SCR diode consists of three terminals namely anode (A), cathode (K), Gate (G). The diode arrow represents the direction of conventional current.



Construction of Silicon Controlled Rectifier

A silicon controlled rectifier is made up of 4 semiconductor layers of alternating P and N type materials, which forms NPNP or PNPN structures. It has three P-N junctions namely J_1, J_2, J_3 with three terminals attached to the semiconductors materials namely anode (A), cathode (K), and gate (G). Anode is a positively charged electrode through which the conventional current enters into an electrical device, cathode is a negatively charged electrode through which the conventional current leaves an electrical device, gate is a terminal that controls the flow of current between anode and cathode. The gate terminal is also sometimes referred to as control terminal.



SCR Structure

The anode terminal of SCR diode is connected to the first p-type material of a PNPN structure, cathode terminal is connected to the last n-type material, and gate terminal is connected to the second p-type material of a PNPN structure which is nearest to the cathode.

In silicon controlled rectifier, silicon is used as an intrinsic semiconductor. When pentavalent impurities are added to this intrinsic semiconductor, an N-type semiconductor is formed. When trivalent impurities are added to an intrinsic semiconductor, a p-type semiconductor is formed.

When 4 semiconductor layers of alternating P and N type materials are placed one over another, three junctions are formed in PNPN structure. In a PNPN structure, the junction J_1 is formed between the first P-N layer, the junction J_2 is formed between the N-P layer and the junction J_3 is formed between the last P-N layer. The doping of PNPN structure is depends on the application of SCR diode

Modes of Operation in SCR

There are three modes of operation for a Silicon Controlled Rectifier (SCR), depending upon the biasing given to it.

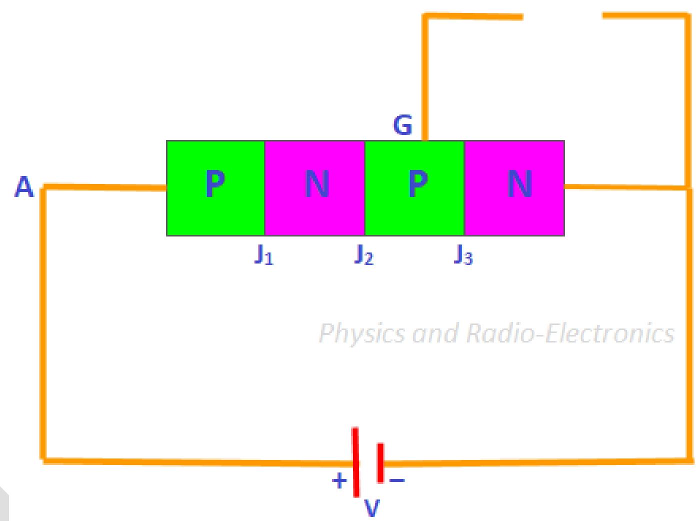
1) Forward Blocking Mode (Off State)

2) Forward Conducting Mode (On State)

3) Reverse Blocking Mode (Off State)

1) Forward Blocking Mode (Off State)

In this mode of operation, the positive voltage (+) is given to anode A (+), negative voltage (-) is given to cathode K (-), and gate G is open circuited as shown in the below figure. In this case, the junction J_1 and junction J_3 are forward biased whereas the junction J2 becomes reverse biased. Due to the reverse bias voltage, the width of depletion region increases at junction J_2. This depletion region at junction J_2 acts as a wall or obstacle between the junction J_1 and junction J_3. It blocks the current flowing between junction J_1 and junction J_3. Therefore, the majority of the current does not flow between junction J_1 and junction J_3. However, a small amount of leakage current flows between junction J_1 and junction J_3.



Forward Blocking Mode of SCR

When the voltage applied to the SCR reaches a breakdown value, the high energy minority carriers causes avalanche breakdown. At this breakdown voltage, current starts flowing through the SCR. But below this breakdown voltage, the SCR offers very high resistance to the current and so it will be in off state.

In this mode of operation, SCR is forward biased but still current does flows through it. Hence, it is named as Forward Blocking Mode.

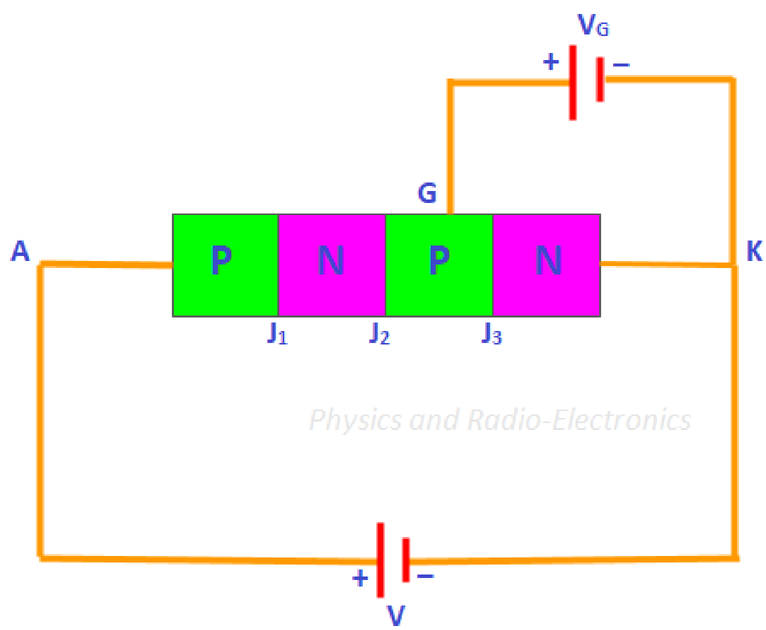
2) Forward Conducting Mode (On State)

The Silicon Controlled Rectifier can be made to conduct in two ways:

i. By increasing the forward bias voltage applied between anode and cathode beyond the breakdown voltage

ii. By applying positive voltage at gate terminal.

In the first case, the forward bias voltage applied between anode and cathode is increased beyond the breakdown voltage, the minority carriers (free electrons in anode and holes in cathode) gains large amount of energy and accelerated to greater velocities. This high speed minority carriers collides with other atoms and generates more charge carriers. Likewise, many collisions happens with other atoms. Due to this, millions of charge carriers are generated. As a result depletion region breakdown occurs at junction J_2 and current starts flowing through the SCR. So the SCR will be in On state. The current flow in the SCR increases rapidly after junction breakdown occurs.



Forward Conducting Mode of SCR

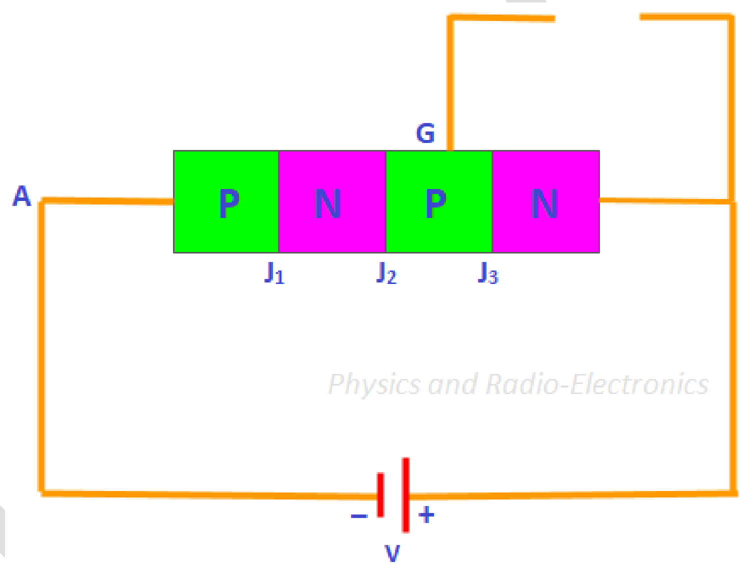
In the second case, a small positive voltage V_G is applied to the gate terminal. As we know that, in forward blocking mode, current does not flows through the circuit because of the wide depletion region present at the junction J_2. This depletion region was formed because of the reverse biased gate terminal. So this problem can be easily solved by applying a small positive voltage at the Gate terminal. When a small positive voltage is applied to the gate terminal, it will become forward biased. So the depletion region width at junction J_2 becomes very narrow. Under this condition, applying a small forward bias voltage between anode and cathode is enough for electric current to penetrate through this narrow depletion region. Therefore, electric current starts flowing through the SCR circuit.

In second case, we no need to apply large voltage between anode and cathode. A small voltage between anode and cathode, and positive voltage to gate terminal is enough to brought SCR from blocking mode to conducting mode.

In this mode of operation, SCR is forward biased and current flows through it. Hence, it is named as Forward Conducting Mode.

3) Reverse Blocking Mode (On State)

In this mode of operation, the negative voltage (-) is given to anode (+), positive voltage (+) is given to cathode (-), and gate is open circuited as shown in the below figure. In this case, the junction J_1 and junction J_3 are reverse biased whereas the junction J2 becomes forward biased.



Reverse Blocking Mode of SCR

As the junctions J_1 and junction J_3 are reverse biased, no current flows through the SCR circuit. But a small leakage current flows due to drift of charge carriers in the forward biased junction J_2. This small leakage current is not enough to turn on the SCR. So the SCR will be in Off state.

V-I CHARACTERISTICS OF SCR

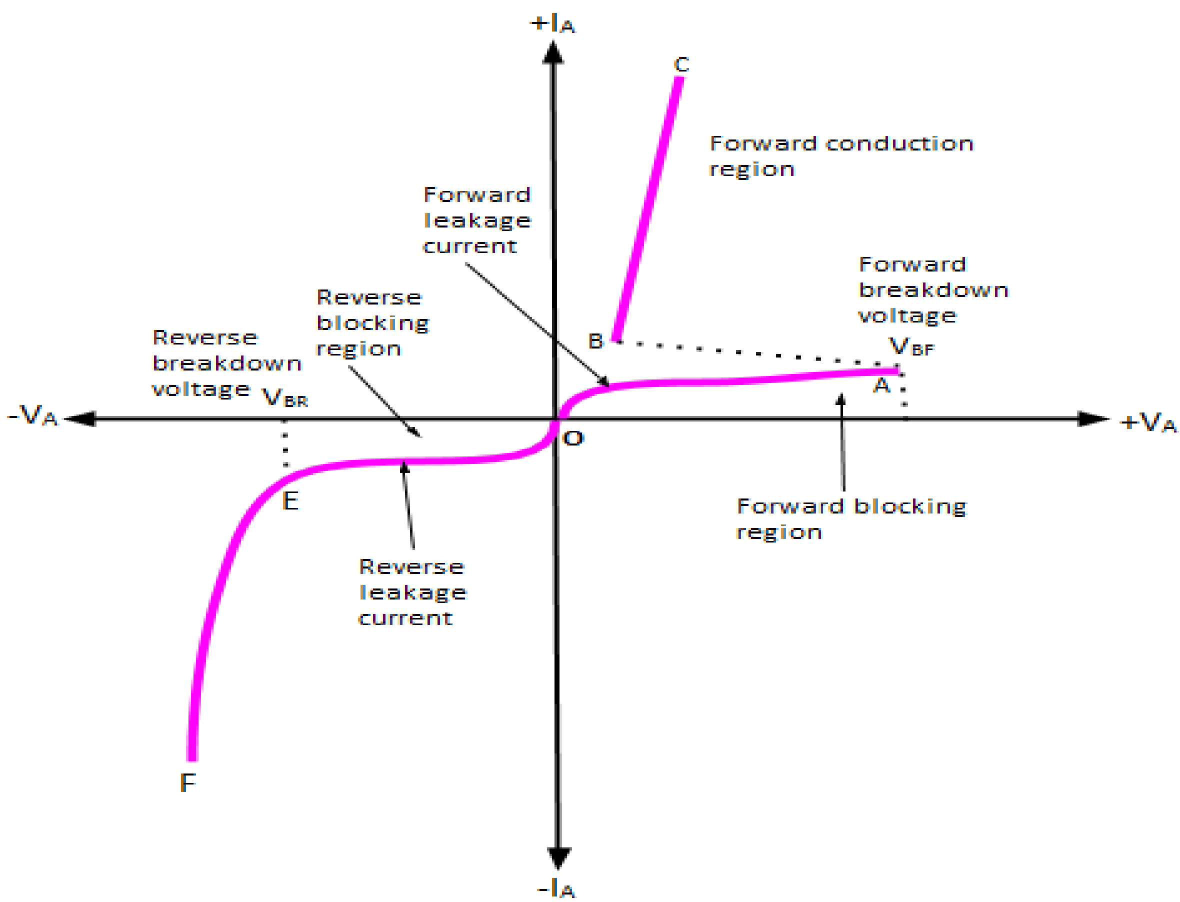
The V-I characteristics of SCR is shown in the below figure. The horizontal line in the below figure represents the amount of voltage applied across the SCR whereas the vertical line represents the amount of current flows in the SCR.

V_A = Anode voltage, I_A = Anode current, $+V_A$ = Forward anode voltage, $+I_A$ = Forward anode current, $-V_A$ = Reverse anode voltage, $+I_A$ = Reverse anode current

The V-I characteristics of SCR is divided into three regions:

- Forward blocking region
- Forward conduction region
- Reverse blocking region
- Forward blocking region

In this region, the positive voltage (+) is given to anode (+), negative voltage (-) is given to cathode (-), and gate is open circuited. Due to this the junction J_1 and J_3 become forward biased while J_2 become reverse biased. Therefore, a small leakage current flows from anode to cathode terminals of the SCR. This small leakage current is known as forward leakage current.



V-I Characteristics of SCR

The region OA of V-I characteristics is known as forward blocking region in which the SCR does not conduct electric current.

- **Forward Conduction region**

If the forward bias voltage applied between anode and cathode is increased beyond the breakdown voltage, the minority carriers (free electrons in anode and holes in cathode) gains large amount of energy and accelerated to greater velocities. This high speed minority carriers collides with other atoms and generates more charge carriers. Likewise, many collisions happens with atoms. Due to this, millions of charge carriers are generated. As a result depletion region breakdown occurs at junction J_2 and current starts flowing through the SCR. So the SCR will be in On state. The current flow in the SCR increases rapidly after junction breakdown occurs.

The voltage at which the junction J_2 gets broken when the gate is open is called forward breakdown voltage (V_{BF}).

The region BC of the V-I characteristics is called conduction region. In this region, the current flowing from anode to cathode increases rapidly. The region AB indicates that as soon as the device becomes on, the voltage across the SCR drops to some volts.

- **Reverse Blocking Region**

In this region, the negative voltage (-) is given to anode (+), positive voltage (+) is given to cathode (-), and gate is open circuited. In this case, the junction J_1 and junction J_3 are reverse biased whereas the junction J2 becomes forward biased.

As the junctions J_1 and junction J_3 are reverse biased, no current flows through the SCR circuit. But a small leakage current flows due to drift of charge carriers in the forward biased junction J_2. This small leakage current is called reverse leakage current. This small leakage current is not sufficient to turn on the SCR.

If the reverse bias voltage applied between anode and cathode is increased beyond the reverse breakdown voltage (V_{BR}), an avalanche breakdown occurs. As a result, the current increases rapidly. The region EF is called reverse avalanche region. This rapid increase in current may damage the SCR device.

Applications of Silicon Controlled Rectifier

The silicon controlled rectifier is used in different applications some which are listed below.

- AC Power Control**:** The Silicon Controlled rectifier is unidirectional device when it is connected to the ac supply then it would be turn on in positive half cycle of ac supply and delivered the power to the load. In negative half cycle of ac supply it would be turn off and do not provide any power to load therefore it can be used as ac power control in power control switches such as fan dimmers, power regulators and motor control etc.

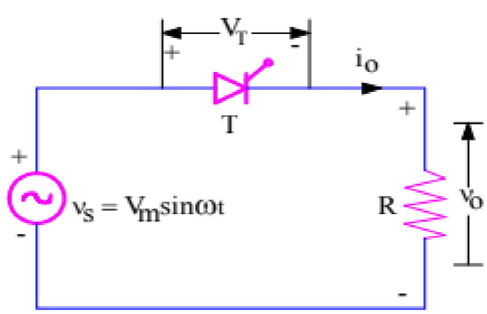
- **Controlled Bridge Rectifiers:** The silicon controlled rectifier is used in ac to dc converters for the rectification of the ac power in dc power such as half wave and full wave rectifiers. These rectifiers power can also be controlled by giving the trigging signal at the gate of SCR
- **DC Power Transmission:** The silicon controlled rectifier is used dc power transmission line for converting the high-power ac in to high power dc.
- **Power Electronic Devices:**The silicon controlled rectifier is used in power electronics devices for controlling the power of switching load.
- The silicon controlled rectifier is also used in different trigging timing and ICs circuits.

SINGLE PHASE HALF WAVE CONTROLLED RECTIFIER WITH R LOAD

Single Phase Half Wave Controlled Rectifier, as the name suggests, is a rectifier circuit which converts AC input into DC output only for positive half cycle of the AC input supply. The word "controlled" means that, we can change the starting point of load current by controlling the firing angle of SCR. These words might seem a lot technical. But firing of SCR simply means, the SCR turn ON at certain point of time when it is forward biased.

Single Phase Half Wave Controlled Rectifier Circuit:

A Single Phase Half Wave Controlled Rectifier circuit consists of SCR / thyristor, an AC voltage source and load. The load may be purely resistive, Inductive or a combination of resistance and inductance. For simplicity, we will consider a resistive load. A simple circuit diagram of Single Phase Half Wave Controlled Rectifier is shown in figure below.



v_0 = Load output voltage

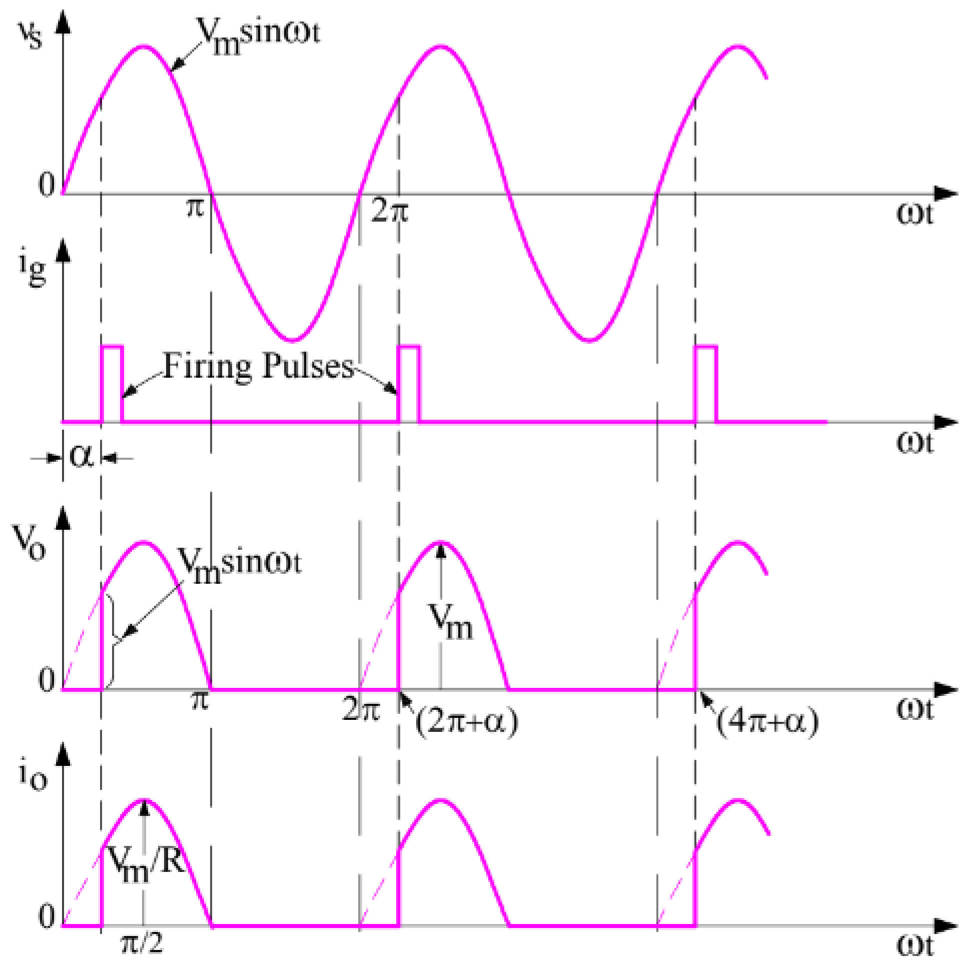
i_0 = Load current

V_T = Voltage across the thyristor T

. Following points must be kept in mind while discussing controlled rectifier:

- The necessary condition for turn ON of SCR is that, it should be forward biased and gate signal must be applied. In other words, an SCR will only get turned ON when it is forward biased and fired or gated.
- SCR will only turn off when current through it reaches below holding current and reverse voltage is applied for a time period more than the SCR turn off time.

Well, let us go ahead with the above points in mind. Let us assume that thyristor T is fired at a firing angle of α. This means when wt = α, gate signal will be applied and SCR will start conducting. Refer the figure below.



Thyristor T is forward biased for the positive half cycle of supply voltage. The load output voltage is zero till SCR is fired. Once SCR is fired at an angle of α, SCR starts conducting. But as soon as the supply voltage becomes zero at ωt = π, the load current will become zero and after ωt = π, SCR is reversed biased. Thus thyristor T will turn off at ωt = π and will remain in OFF condition till it is fired again at ωt = (2π+α).

Therefore, the load output voltage and current for one complete cycle of input supply voltage may be written as

$v_0 = V_m \text{Sin}\omega t$ for $\alpha \le \omega t \le \pi$

$i_0 = V_m \text{Sin}\omega t \,/\, R$ for for $\alpha \le \omega t \le \pi$

Calculation of Average Load Output Voltage:

As we know that, average value of any function f(x) cab be calculated using the formula

$$Average\ Value = (1/T)\int_0^T f(x)dx$$

Let us now calculate the average value of output voltage for Single Phase Half Wave Controlled Rectifier.

$$Average\ Value\ of\ Load\ output\ Voltage$$

$$= (1/2\pi)\int_0^{2\pi} VmSin\omega td(\omega t)$$

$$= (1/2\pi)\int_0^{\alpha} VmSin\omega td(\omega t) + \int_{\alpha}^{\pi} VmSin\omega td(\omega t) + \int_{\pi}^{2\pi} VmSin\omega td(\omega t)$$

Since the value of load output voltage is zero from $0 \le \omega t \le \alpha$ and $\pi < \omega t < 2\pi$, therefore

$$= (1/2\pi)\int_{\alpha}^{\pi} VmSin\omega td(\omega t)$$

$$= (Vm/2\pi)\int_{\alpha}^{\pi} Sin\omega td(\omega t)$$

$$= \left(\frac{Vm}{2\pi}\right)[1 + Cos\alpha]$$

For Single Phase Half Wave Controlled Rectifier:

$$Average\ Value\ of\ Load\ output\ Voltage$$

$$= \left(\frac{Vm}{2\pi}\right)[1 + Cos\alpha]$$

From the expression of average output voltage, it can be seen that, by changing firing angle α, we can change the average output voltage. The average output voltage is maximum when firing angle is zero and it is minimum when firing angle α = π. This is the reason, it is called phase controlled rectifier.

Average load current for Single Phase Half Wave Controlled Rectifier can easily be calculated by dividing the average load output voltage by load resistance R.

Let us now calculate the root mean square (rms) value of load voltage.

$$RMS\ Value = \sqrt{(1/T)\int_0^T [f(x)]^2 dx}$$

$$RMS\ Value\ of\ Load\ output\ Voltage$$

$$= \sqrt{(1/2\pi)\int_0^{2\pi} [VmSin\omega t]^2 d(\omega t)}$$

$$= \sqrt{(Vm/4\pi)\int_0^{2\pi} [2Sin\omega t]^2 d(\omega t)}$$

$$= \sqrt{(Vm/4\pi)\int_0^{2\pi} [1 - Cos2\omega t] d(\omega t)}$$

Since the value of load output voltage is zero from $0 \le \omega t \le \alpha$ and $\pi < \omega t < 2\pi$, therefore

$$= \sqrt{(Vm/4\pi)\int_\alpha^{\pi} [1 - Cos2\omega t] d(\omega t)}$$

$$= \left(\frac{Vm}{2\sqrt{\pi}}\right)\sqrt{(\pi - \alpha) + (1/2)Sin2\alpha}$$

$$RMS\ Value\ of\ Load\ output\ Voltage$$

$$= \left(\frac{Vm}{2\sqrt{\pi}}\right)\sqrt{(\pi - \alpha) + (1/2)Sin2\alpha}$$

RMS value of load current can be calculated by dividing the rms load voltage by resistance R. This means,

RMS Load Current I_{0rms}= RMS Load Voltage / R

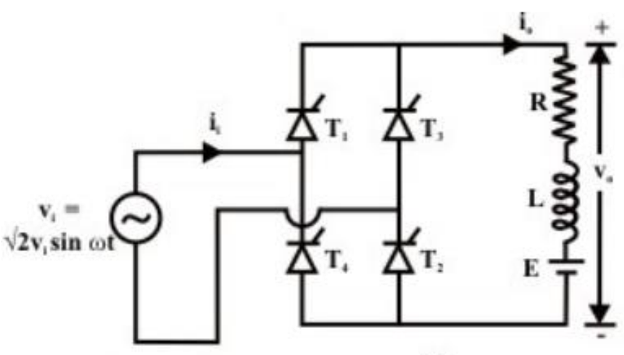
Input volt ampere can be calculated as

Input Volt Ampere

= RMS Supply Voltage x RMS Load Current

= $V_s x I_{0rms}$

SINGLE PHASE FULLY CONTROLLED BRIDGE RECTIFIER WITH R LOAD



(a)

MODE / DEVICE	T_1	T_2	T_4	T_3	v_0
T_1T_2	0	0	$-v_i$	$-v_i$	v_i
T_3T_4	v_i	v_i	0	0	$-v_i$
NONE	$\frac{v_i - E}{2}$	$\frac{v_i + E}{2}$	$-\frac{v_i + E}{2}$	$-\frac{v_i + E}{2}$	E

(b)

Single phase fully controlled bridge converter Fig 10.3 (a) shows the circuit diagram of a single phase fully controlled bridge converter. It is one of the most popular converter circuits and is widely used in the speed control of separately excited dc machines.

Indeed, the R–L–E load shown in this figure may represent the electrical equivalent circuit of a separately excited dc motor. The single phase fully controlled bridge converter is obtained by replacing all the diode of the corresponding uncontrolled converter by thyristors. Thyristors T1 and T2 are fired together while T3 and T4 are fired 180º after T1 and T2. From the circuit diagram of Fig 10.3(a) it is clear that for any load current to flow at least one thyristor from the top group (T1, T3) and one thyristor from the bottom group (T2, T4) must conduct. It can also be argued that neither T1T3 nor T2T4 can conduct simultaneously. For example whenever T3 and T4 are in the forward blocking state and a gate pulse is applied to them, they turn ON and at the same time a negative voltage is applied across T1 and T2 commutating them immediately. Similar argument holds for T1 and T2.

For the same reason T1T4 or T2T3 can not conduct simultaneously. Therefore, the only possible conduction modes when the current i0 can flow are T1T2 and T3T4. Of coarse it is possible that at a given moment none of the thyristors conduct. This situation will typically occur when the load current becomes zero in between the firings of T1T2 and T3T4. Once the load current becomes zero all thyristors remain off. In this mode the load current remains zero. Consequently the converter is said to be operating in the discontinuous conduction mode.

Fig 10.3(b) shows the voltage across different devices and the dc output voltage during each of these conduction modes. It is to be noted that whenever T1 and T2 conducts, the voltage across T3 and T4 becomes –vi. Therefore T3 and T4 can be fired only when vi is negative i.e, over the negative half cycle of the input supply voltage. Similarly T1 and T2 can be fired only over the positive half cycle of the input supply. The voltage across the devices when none of the thyristors conduct depends on the off state impedance of each device. The values listed in Fig 10.3 (b) assume identical devices.

Under normal operating condition of the converter the load current may or may not remain zero over some interval of the input voltage cycle. If i0 is always greater than zero then the converter is said to be operating in the continuous conduction mode. In this mode of operation of the converter T1T2 and T3T4 conducts for alternate half cycle of the input supply.

However, in the discontinuous conduction mode none of the thyristors conduct over some portion of the input cycle. The load current remains zero during that period

Operation in the continuous conduction mode

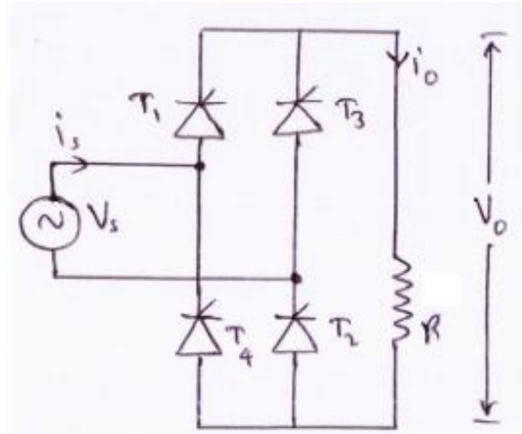
As has been explained earlier in the continuous conduction mode of operation i0 never becomes zero, therefore, either T1T2 or T3T4 conducts. Fig 10.4 shows the waveforms of different variables in the steady state. The firing angle of the converter is α. The angle θ is given by

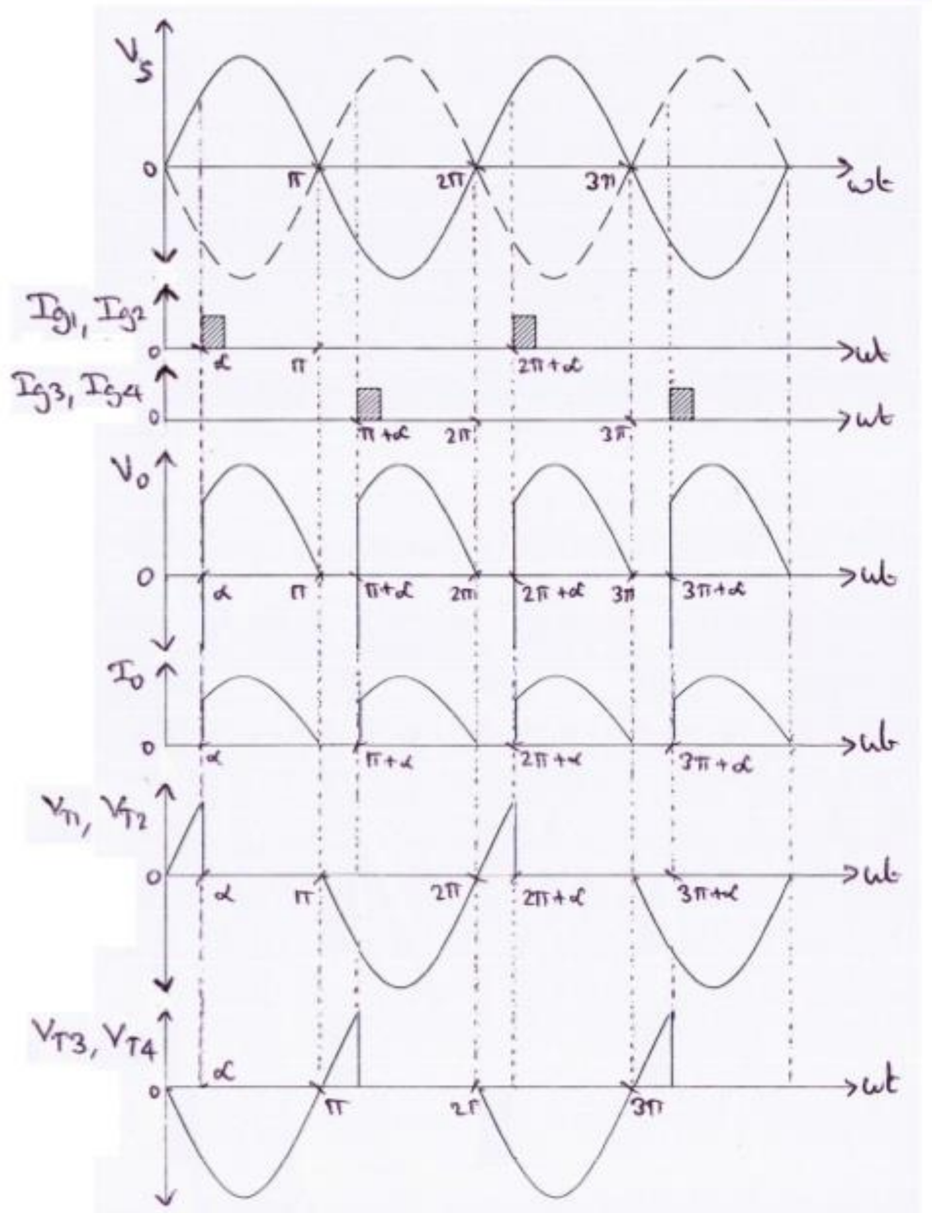
$$\sin\theta = \frac{E}{\sqrt{2}V_i}$$

It is assumed that at t = 0- T3T4 was conducting. As T1T2 are fired at ωt = α they turn on commutating T3T4 immediately. T3T4 are again fired at ωt = π + α. Till this point T1T2 conducts. The period of conduction of different thyristors are pictorially depicted in the second waveform (also called the conduction diagram) of Fig

1φ full wave bridge converter (fully controlled)

R - LOAD





The dc link voltage waveform shown next follows from this conduction diagram and the conduction table shown in Fig 10.3(b). It is observed that the emf source E is greater than the dc link voltage till $\omega t = \alpha$. Therefore, the load current i0 continues to fall till this point. However, as T1T2 are fired at this point v0 becomes greater than E and i0 starts increasing through R-L and E. At $\omega t = \pi - \theta$ v0 again equals E. Depending upon the load circuit parameters io reaches its maximum at around this point and starts falling afterwards. Continuous conduction mode will be possible only if i0 remains greater than zero till T3T4 are fired at $\omega t = \pi + \alpha$ where upon the same process repeats. The resulting i0 waveform is shown below v0. The input ac current waveform ii is obtained from i0 by noting that whenever T1T2 conducts ii = i0 and ii = - i0 whenever T3T4 conducts. The last waveform shows the typical voltage waveform across the thyristor T1. It is to be noted that when the thyristor turns off at $\omega t = \pi + \alpha$ a negative voltage is applied across it for a duration of $\pi - \alpha$. The thyristor must turn off during this interval for successful operation of the converter

NOTE:

- The single phase fully controlled rectifier allows conversion of single phase AC into DC. Normally this is used in various applications such as battery charging, speed control of DC motors and front end of UPS (Uninterruptible Power Supply) and SMPS (Switched Mode Power Supply)
- All four devices used are thyristors. The turn-on instants of these devices are dependent on the firing signals that are given. Turn-off happens when the current through the device reaches zero and it is reverse biased at least for duration equal to the turn-off time of the device specified in the data sheet.
- In positive half cycle thyristors T1 & T2 are fired at an angle α .
- When T1 & T2 conducts
- Vo=Vs
  IO=is=Vo/R=Vs/R
- In negative half cycle of input voltage, SCR's T3 &T4 are triggered at an angle of (π+α)
- Here output current & supply current are in opposite direction
- ∴ is=-io
- T3 & T4 becomes off at 2π.

Magnitude of Output Voltage and Current

Let the input voltage Vi1 be a sinusoidal voltage of amplitude Vm and frequency f Hz and let it be given by,

$V_{i1} = V_m \sin\omega t = V_m \sin\theta$ ………..(1)

Let, α be the firing angle during the positive half cycle. Then SCR_1 conducts during angle α to π radians during the positive half cycle. Hence the average output voltage

V_{av1} contributed by SCR_1 is given by,

$$V_{av1} = \frac{1}{2\pi} \int_{\alpha}^{\pi} V_m Sin\theta d\theta \quad \text{………(2)}$$

Similarly, the average voltage contributed by SCR_2 due to input voltage V_{i2} is equal to V_{av1}. Hence, the total value of average output voltage V_{av} is given by,

$$V_{av} = \frac{1}{\pi} \int_{a}^{\pi} V Sin\theta d\theta \quad \text{……..(3)}$$

$$= \frac{V_m}{\pi} [-Cos\theta]_{\alpha}^{pi}$$

$$= \frac{V_m}{\pi} (1 + Cos\alpha) \quad \text{…….(4)}$$

Average output current is,

$$I_{av} = \frac{V_{av}}{R_L} = \frac{V_m}{\pi R_L} (1 + cos\alpha) \quad \text{………(5)}$$

We thus, find that fullwave SCR rectifier produces average output voltage and average output current twice those in half wave SCR rectifier. Further, removal of ripple voltage by filter circuit is more effective in full wave SCR rectifier.

INVERTERS

An inverter refers to a power electronic device that converts power in DC form to AC form at the required frequency and voltage output.

Inverters are classified into two main categories −

- **Voltage Source Inverter** − The voltage source inverter has stiff DC source voltage that is the DC voltage has limited or zero impedance at the inverter input terminals.
- **Current Source Inverter** − A current source inverter is supplied with a variable current from a DC source that has high impedance. The resulting current waves are not influenced by the load.

Single Phase Inverter

There are two types of single phase inverters − full bridge inverter and half bridge inverter.

Half Bridge Inverter

This type of inverter is the basic building block of a full bridge inverter. It contains two switches and each of its capacitors has a voltage output equal to *[Math Processing Error]Vdc2*. In addition, the switches complement each other, that is, if one is switched ON the other one goes OFF.

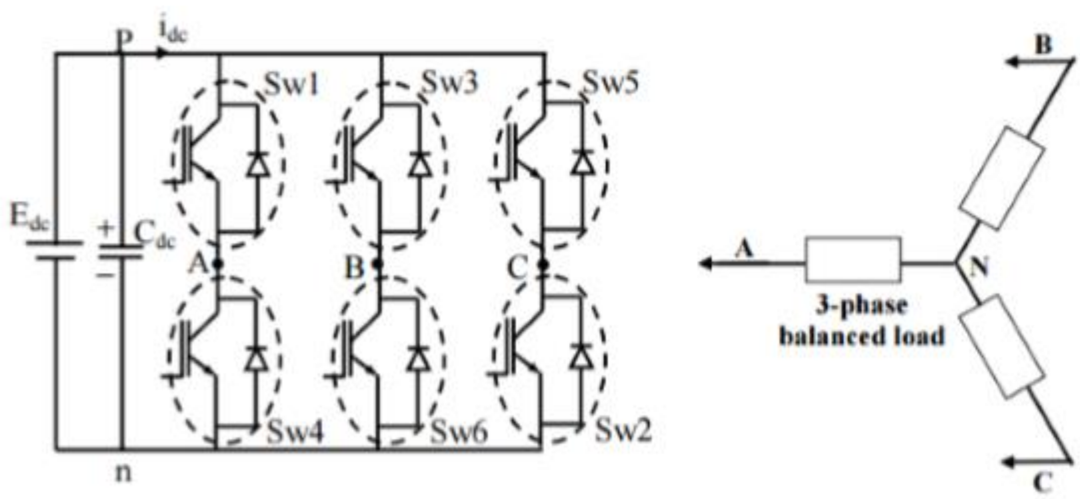
Full Bridge Inverter

This inverter circuit converts DC to AC. It achieves this by closing and opening the switches in the right sequence. It has four different operating states which are based on which switches are closed.

Three Phase Inverter

A three-phase inverter converts a DC input into a three-phase AC output. Its three arms are normally delayed by an angle of 120° so as to generate a three-phase AC supply. The inverter switches each has a ratio of 50% and switching occurs after every T/6 of the time T. The switches S1 and S4, the switches S2 and S5 and switches S3 and S6 complement each other.

The figure below shows a circuit for a three phase inverter. It is nothing but three single phase inverters put across the same DC source. The pole voltages in a three phase inverter are equal to the pole voltages in single phase half bridge inverter.

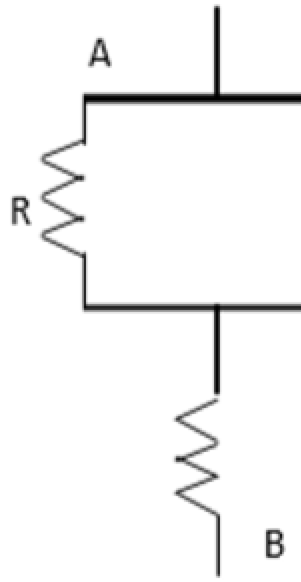


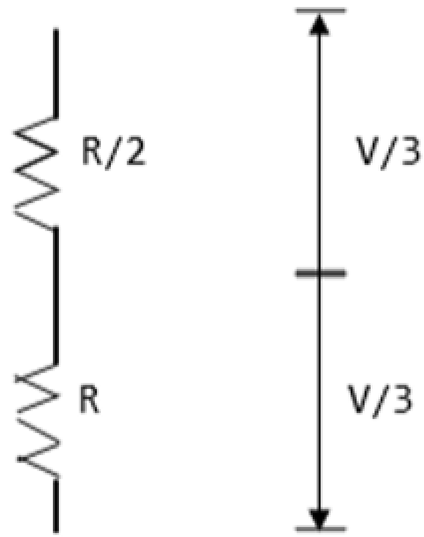
The two types of inverters above have two modes of conduction − **180° mode of conduction** and **120° mode of conduction**.

180° mode of conduction

In this mode of conduction, every device is in conduction state for 180° where they are switched ON at 60° intervals. The terminals A, B and C are the output terminals of the bridge that are connected to the three-phase delta or star connection of the load.

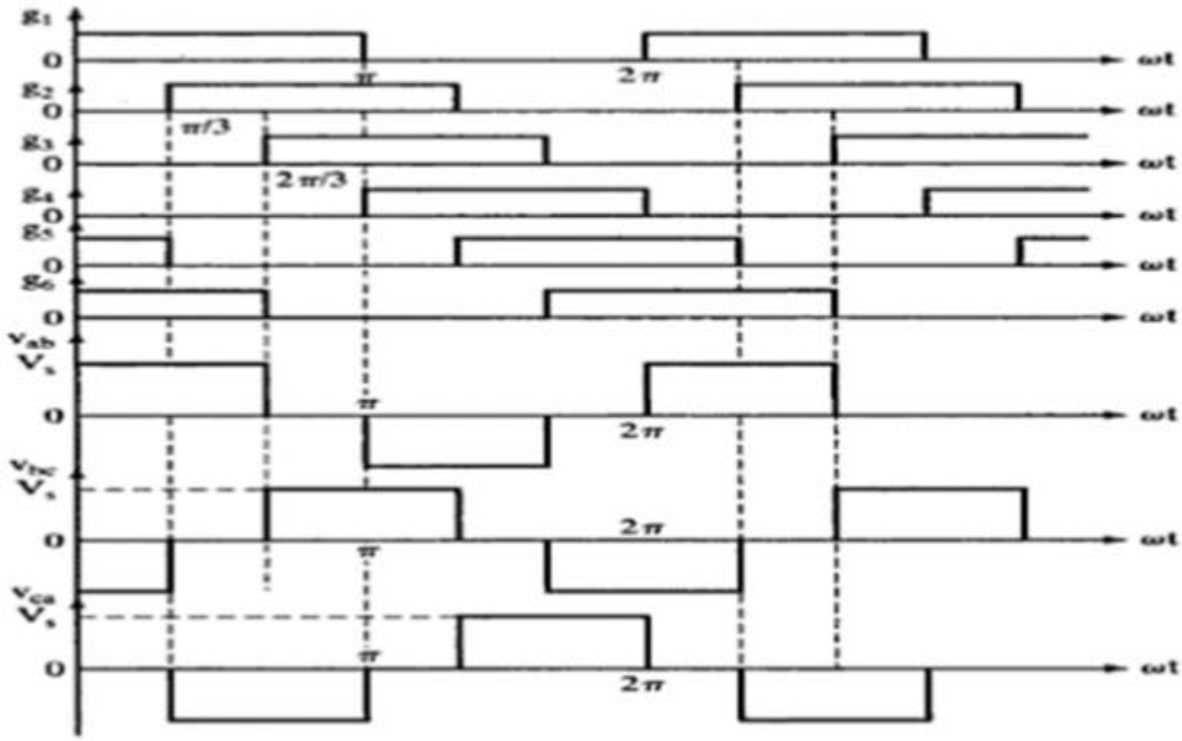
The operation of a balanced star connected load is explained in the diagram below. For the period 0° − 60° the points S1, S5 and S6 are in conduction mode. The terminals A and C of the load are connected to the source at its positive point. The terminal B is connected to the source at its negative point. In addition, resistances R/2 is between the neutral and the positive end while resistance R is between the neutral and the negative terminal.





The load voltages are gives as follows; $V_{AN} = V/3$, $V_{BN} = -2V/3$, $V_{CN} = V/3$	The line voltages are given as follows; $V_{AB} = V_{AN} - V_{BN} = V$, $V_{BC} = V_{BN} - V_{CN} = -V$, $V_{CA} = V_{CN} - V_{AN} = 0$

Waveforms for 180° mode of conduction



120° mode of conduction

In this mode of conduction, each electronic device is in a conduction state for 120°. It is most suitable for a delta connection in a load because it results in a six-step type of waveform across any of its phases. Therefore, at any instant only two devices are conducting because each device conducts at only 120°.

The terminal A on the load is connected to the positive end while the terminal B is connected to the negative end of the source. The terminal C on the load is in a condition called floating state. Furthermore, the phase voltages are equal to the load voltages as shown below.

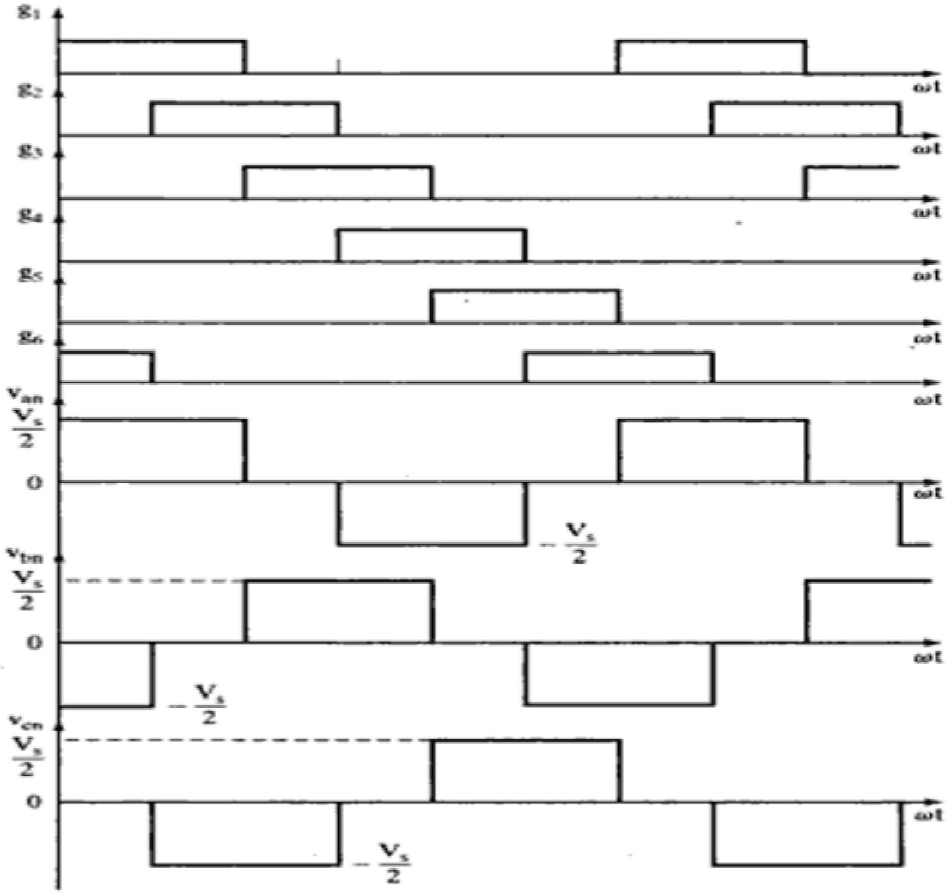
Phase voltages = Line voltages

$V_{AB} = V$

$V_{BC} = -V/2$

$V_{CA} = -V/2$

Waveforms for 120° mode of conduction



Applications of Inverter

These are used in a variety of applications like tiny car adapters to the office, household applications, as well as large-grid systems.

- Inverters can be used as an UPS-Uninterruptible power supplies
- These can be used as standalone inverters
- These can be used in solar power systems
- An inverter is the basic building block of an SMPS- switched mode power supply.
- These can be used in Centrifugal fans, pumps, mixers, extruders, test stands. conveyors, metering pumps. and Web-handling equipment.

MODULE 5

ELECTRIC DRIVES

INTRODUCTION TO ELECTRIC DRIVES

Drive:

A combination of prime mover, transmission equipment and mechanical Working load is called a drive

Electric drive:

An Electric Drive can be defined as an electromechanical device for converting electrical energy to mechanical energy to impart motion to different machines and mechanisms for various kinds of process control.

BLOCK DIAGRAM OF AN ELECTRICAL DRIVES

The basic block diagram for electrical drives used for the motion control is shown in the following figure

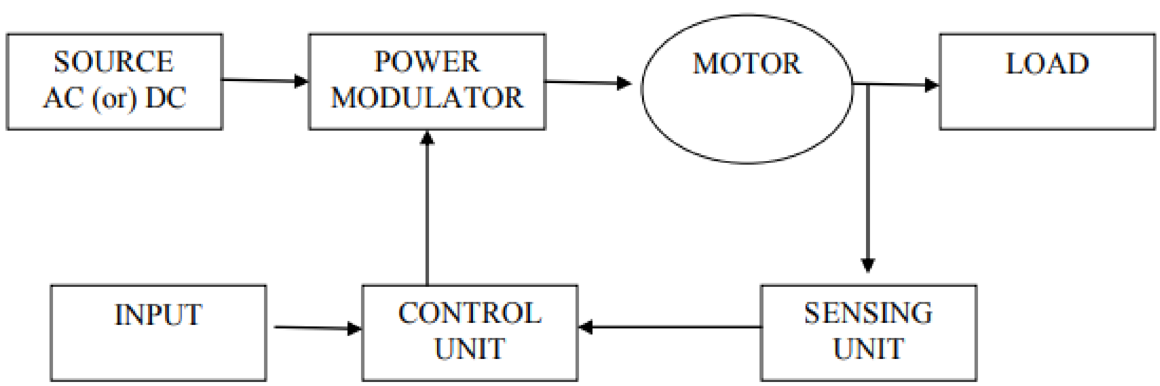


Fig 1.1 Block Diagram for Electrical Drives

The aggregate of the electric motor, the energy transmitting shaft and the control equipment by which the motor characteristics are adjusted and their operating conditions with respect to mechanical load varied to suit practical requirements is called as electric drive.

Drive system=Drive + load

BASIC COMPONENT (or) ELEMENTS OF ELETCRIC DRIVES

Block diagram of electric drive:

Load:

usually a machinery to accomplish a given task. Eg-fans, pumps, washing machine etc.

Power modulator:

modulators (adjust or converter) power flow from the source to the motion

Motor:

actual energy converting machine (electrical to mechanical)

Source:

energy requirement for the operation the system.

Control:

adjust motor and load characteristics for the optimal mode.

Power modulators:

Power modulators regulate the power flow from source to the motor to enable the motor to develop the torque speed characteristics required by the load.

The common function of the power modulator is,

- They contain and control the source and motor currents with in permissible limits during the transient operations such as starting, braking, speed reversal etc.
- They converts the input electrical energy into the form as required by the motors.
- Adjusts the mode of operation of the motor that is motoring, braking are regenerative.

Power modulators may be classified as,

1. Converters uses power devices to convert uncontrolled valued to controllable output.

2. Switching circuits switch mode of operation
3. Variable impedance

Converters

They provide adjustable voltage/current/frequency to control speed, torque output power of the motor.

The various type of converters are,

- AC to DC rectifiers
- DC to DC choppers
- AC to AC choppers
- AC to AC –AC voltage controllers (voltage level is controlled)
- Cyclo converter (Frequency is controlled)
- DC to AC inverters

Switching circuits

Switching circuits are needed to achieve any one of the following.

- Changing motor connection to change its quadrant of operation.
- Changing motor circuits parameters in discrete steps for automatic starting and braking control.
- For operating motors and drives according to a predetermine sequence
- To provide inter locking their by preventing maloperation
- Disconnect under up normal condition

  Eg: electromagnetic contacters, PLC in sequencing and inter locking operation, solid state relays etc.

Advantages of Electrical Drives

The advantages of electrical drives include the following.

- These dries are obtainable with an extensive range of speed, power & torque.
- Not like other main movers, the requirement of refuel otherwise heat up the motor is not necessary.
- They do not contaminate the atmosphere.

- Previously, the motors like synchronous as well as induction were used within stable speed drives. Changeable speed drives utilize a dc motor.
- They have flexible manage characteristics due to the utilization of electric braking.
- At present, the AC motor is used within variable speed drives because of semiconductor converters development.

Disadvantages of Electrical Drive

The disadvantages of electrical drives include the following.

- This drive cannot be used where the power supply is not accessible.
- The power breakdown totally stops the entire system.
- The primary price of the system is expensive.
- The dynamic response of this drive is poor.
- The drive output power which is obtained is low.
- By using this drive noise pollution can occur.

Applications of Electrical Drives

The applications of electrical drives include the following.

- The main application of this drive is electric traction which means transportation of materials from one location to another location. The different types of electric tractions mainly include electric trains, buses, trolleys, trams, and solar-powered vehicles inbuilt with battery.
- Electrical drives are extensively used in the huge number of domestic as well as industrial applications which includes motors, transportation systems, factories, textile mills, pumps, fans, robots, etc.
- These are used as main movers for petrol or diesel engines, turbines like gas otherwise steam, motors like hydraulic & electric.

CHOICE OF ELECTRIC DRIVES

- **Nature of electric supply**

  Whether AC or DC supply is to be used for supply

- **Nature of the drive**

  Whether the particular motor is going to drive individual machine or a group of machines

- **Capital and running cost**

  Maintenance requirement

  Space ad weight restrictions

  Environment and location

- **Nature of load**
  1. Whether the load requires light or heavy starting torque
  2. Whether load torque increases with speed remain constant
  3. Whether the load has heavy inertia which may require longer straight time
- **Electrical characteristics of motor**
  1. Starting characteristics,
  2. running characteristics,
  3. speed control and
  4. Braking characteristics
- **Size, rating and duty cycle of motors**
  1. Whether the motor is going to the operator for a short time or whether it has to run continuously intermittently or on a variable load cycle
- **Mechanical considerations**
  1. Type of enclosures, type of bearings, transmission of drive and Noise level.
  2. Due to practical difficulties, it may not possible to satisfy all the above considerations.

     In such circumstances, it is the experience and knowledge background which plays a vital role in the selection of the suitable drive.

The following points must be given utmost important for the selection of motor.

The factors are:

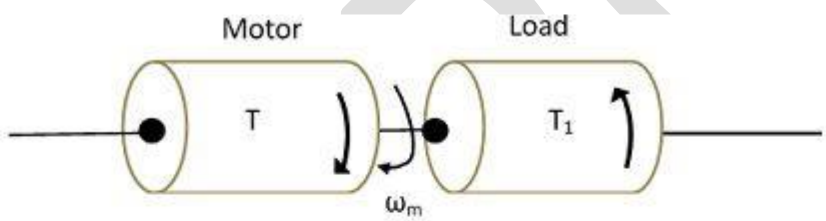
- Nature of the mechanical load driven

- Matching of the speed torque characteristics of the motor with that of the load
- Starting conditions of the load.

DYNAMICS OF ELECTRICAL DRIVES

When the motor rotates, the load of the system may rotate or may go through a translational motion. In the translational motion, the position of the body changes from point to point in space. The speed of the load may be different from that of the motor.

If the load has different parts, their speed may be different. Some part of the rotor may rotate while others may go through a translational motion. The equivalent load system of the motor is shown in the figure below.



Equivalent Motor Load System

Here,
J = Polar moment of inertia of motor load

W_m = Instantaneous angular velocity

T = Instantaneous value of developed motor torque

T_1 = Instantaneous value of load torque referred to motor shaft

The equation shown below described the motor load equation. This equation is applicable for variable inertia drives such as mine, winders, reel, drives, industrial robots. In this equation, the load torque includes friction and windage torque of the motor.

$$T - T_1 = \frac{d}{dt}(J\omega_m) = J\frac{d\omega_m}{dt} + \omega_m\frac{dJ}{dt}$$

For constant inertia drive dj/dt = 0. Therefore the equation becomes

$$T = T_1 + \frac{d}{dt}(J\omega_m)$$

Fundamental Torque Equation

The above equation shows that the load developed by the motor is counter-balanced by a load torque T_1 and a dynamic torque $jd\omega_m t/dt$.The torque component $j(d\omega_m t/dt)$ is called dynamic torque because it is present only during transient operations.

The acceleration or deacceleration of the drive mainly depends on whether the load torque is greater or less than the motor torque. During acceleration, the motor supplies the load torque along with an additional torque component $jd\omega_m t/dt$ to overcome the drive inertia.

The drives which have a large inertia must increase the load torque by a large amount for getting sufficient acceleration. The drive which requires a fast transient response, their motor torque should be maintained at the excessive value and motor load system should be designed with a lower possible inertia.

The energy associated with dynamic torque is stored in the form of kinetic energy and given by the equation $jd\omega^2_m/dt$. During the deacceleration, the dynamic torque has a negative sign. Thus it assists the motor developed torque T and maintains the drive motion by extracting energy from stored kinetic energy.

CLASSIFICATION OF LOAD TORQUE

1.Active Load torques

2.Passice Load torques

Active Load Torques:

Load torques which have the potential to drive the motor under equilibrium conditions are called active load torques.

Load torques usually retain sign when the drive rotation is changed.

Passive Torque:

Load torques which always oppose the motion and change their sign on the reversal of motion are called passive load torques.

Torque due to friction cutting – Passive torque.

Components of load torques:

1.Friction Torque (TF)

The friction torque (TF) is the equivalent value of various friction torques referred to the motor shaft.

2.Windage Torque (Tw)

When a motor runs, the wind generates a torque opposing the motion . This is known as the winding torque.

3.Torque required to do useful mechanical work (Tm)

Nature of this Components of Load Torques depends on particular application. It may be constant and independent of speed; it may be some function of speed; it may depend on the position or path followed by load; it may be time invariant or time-variant; it may vary cyclically and its nature may also change with the load's mode of operation.

Nature of the torque depands of type of load.

It may be constant and indeoendent of speed, Some function of speed, may be time invariant or time variant.

The nature of the torque may change with the change in the loads mode of operation.

Characteristics of different types of load:

In electric drives the driving equipment is an electric motor.

Selection of particular type of motor driving a m/c is the matching of speed-torque charal of the driven unit and that of the motor.

Different types of loads exhibit different speed torque charal.

Most of the industrial loads can be classified into the following 4 general categories:

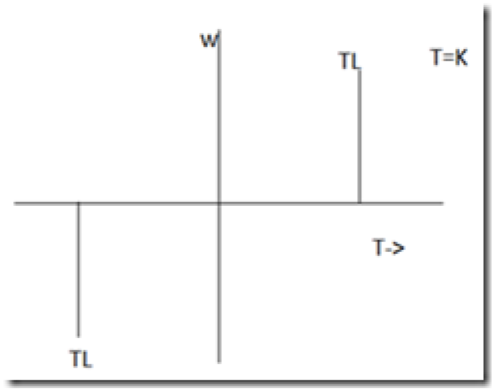
1. Constant torque type load.

2. Torque proportional to speed (generator type load)

3. Torque proportional to square of the speed (fan type load)

4. Torque inversely proportional to speed (const power type load)

1.Constant Torque Characteristic :

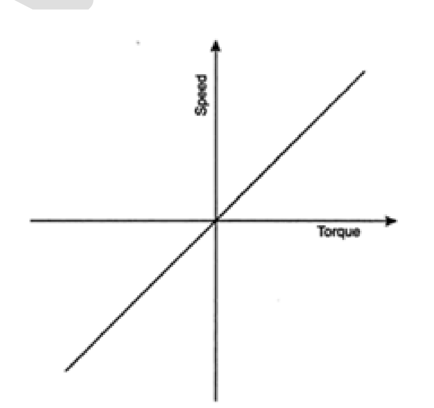


The speed – torque characteristic of this type of load is given by T=K.

Working motor have each mechanical nature of work like shaping , cutting, grinding or sharing, require constant torque irrespective of speed. Similarly cranes during the hoisting.

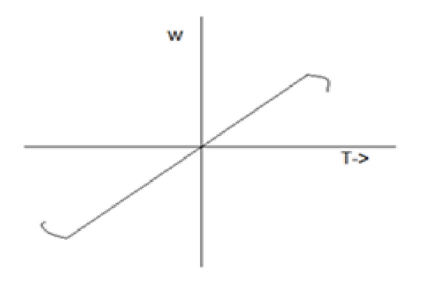
Similarly cranes during the hoisting and conveyors handling constant weight of material / unit, time also exhibit this type of characteristics.

Torque proportional to speed:



Separately excuted dc generators connected to a constant resistance load, eddy current brakes and calendaring m/cs have a speed torque characteristics m/cs have a speed – torque characteristics given by T= Kw.

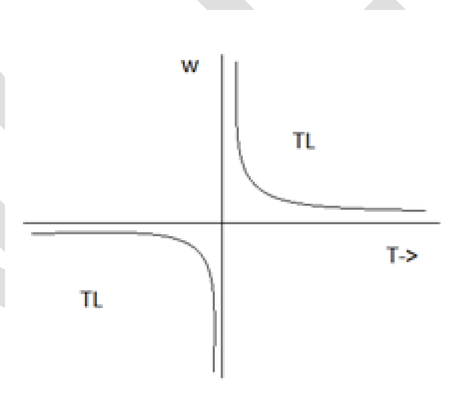
Torque propositional to square of the speed :



Load Torque Square of speed

Example : Fans , Rotary pumps , compressors , ship propellers. The speed – torque characteristics of this type of load is given by

Torque inversely propositional to speed:



· In such types of loads , torque is inversely proportional to speed or load power remains constant.

· Eq: Lathes, boring m/cs, milling m/cs , steel mill colier and electric traction load.

· This type of characteristics is given by

· Most of the load require extra effort at the time of starting to overcome static friction. In power application it is known as brake away torque and load control engineers call it "stiction" .

Because of slition , the speed torque characteristics of the load is modified near to zero speed.

MULTI QUADRANT OPERATION:

For consideration of multi quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed.

A motor operates in two modes – Motoring and braking. In motoring, it converts electrical energy into mechanical energy, which supports its motion .In braking it works as a generator converting mechanical energy into electrical energy and thus opposes the motion.

Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure. A decrease in speed causes the load torque to become greater than the motor torque, electric drive decelerates and operating point moves away from point B.

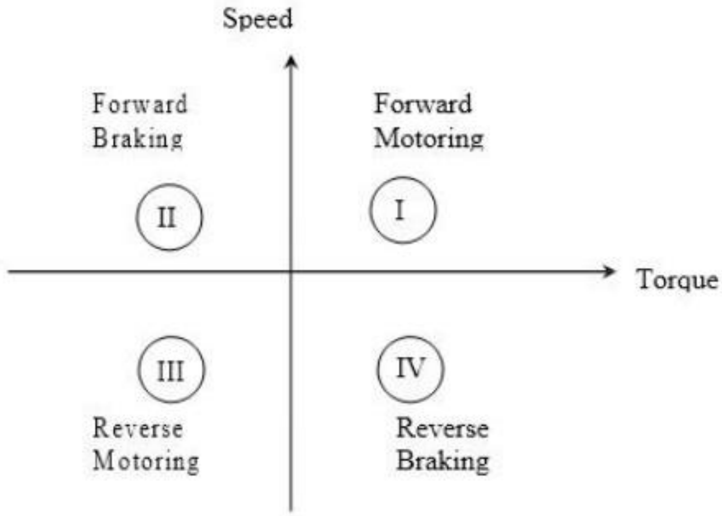
Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B

Similarly operation in quadrant III and IV can be identified as reverse motoring and reverse braking since speed in these quadrants is negative.

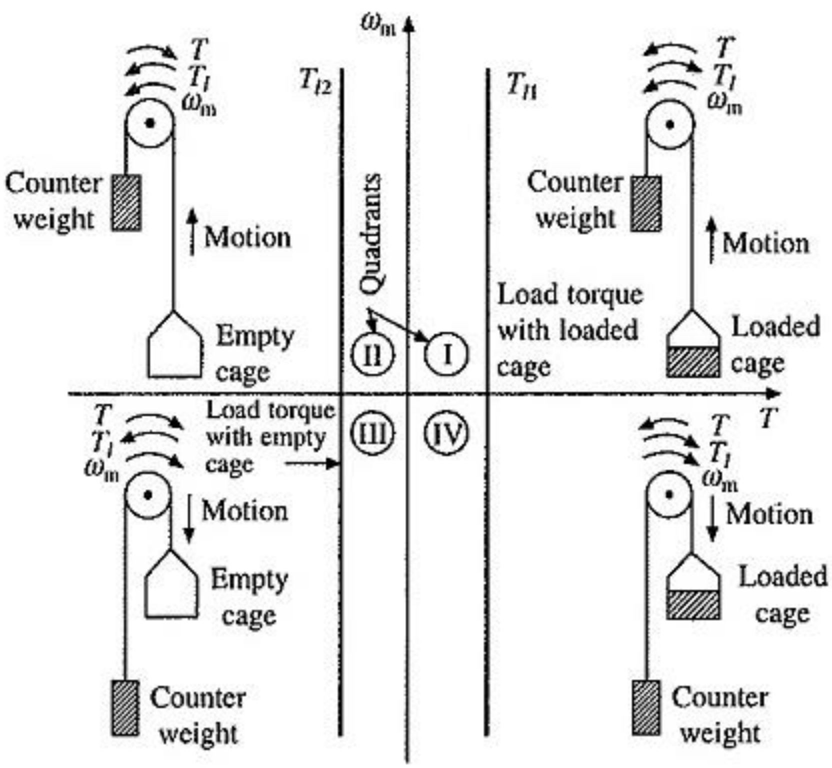
For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction of motor and load torques and direction of speed are marked by arrows

The figure at the right represents a DC motor attached to an inertial load. Motor can provide motoring and braking operations for both forward and reverse directions.

Figure shows the torque and speed co-ordinates for both forward and reverse motions. Power developed by a motor is given by the product of speed and torque. For motoring operations Power developed is positive and for braking operations power developed is negative.



For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction of motor and load torques and direction of speed are marked by arrows.



A hoist consists of a rope wound on a drum coupled to the motor shaft one end of the rope is tied to a cage which is used to transport man or material from one level to another level . Other end of the rope has a counter weight. Weight of the counter weight is chosen to be higher than the weight of empty cage but lower than of a fully loaded cage.

Forward direction of motor speed will be one which gives upward motion of the cage. Load torque line in quadrants I and IV represents speed-torque characteristics of the loaded hoist. This torque is the difference of torques due to loaded hoist and counter weight. The load torque in quadrants II and III is the speed torque characteristics for an empty hoist.

This torque is the difference of torques due to counter weight and the empty hoist. Its sigh is negative because the counter weight is always higher than that of an empty cage. The quadrant I operation of a hoist requires movement of cage upward, which corresponds to the positive motor speed which is in counter clockwise direction here. This motion will be obtained if the motor products positive torque in CCW direction equal to the magnitude of load torque T_{L1}.

Since developed power is positive, this is forward motoring operation. Quadrant IV is obtained when a loaded cage is lowered. Since the weight of the loaded cage is higher than that of the counter weight

.It is able to overcome due to gravity itself.

In order to limit the cage within a safe value, motor must produce a positive torque T equal to T_{L2} in anticlockwise direction. As both power and speed are negative, drive is operating in reverse braking operation. Operation in quadrant II is obtained when an empty cage is moved up. Since a counter weigh is heavier than an empty cage, its able to pull it up.

In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{L2} in clockwise direction. Since speed is positive and developed power is negative, it’s forward braking operation.

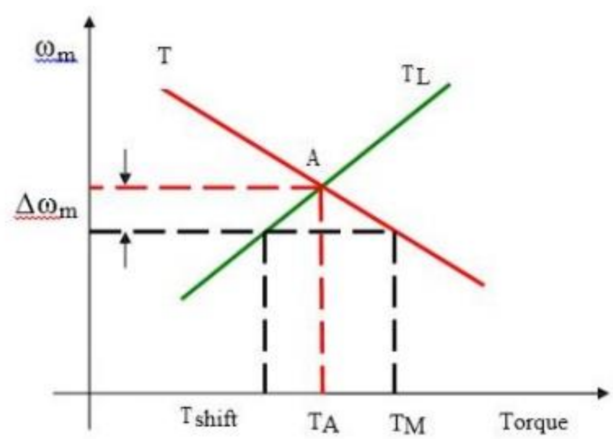
Operation in quadrant III is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in CW direction. Since speed is negative and developed power is positive, this is reverse motoring operation. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient state operation.

STEADY STATE STABILITY:

Equilibrium speed of motor-load system can be obtained when motor torque equals the load torque. Electric drive system will operate in steady state at this speed, provided it is the speed of stable state equilibrium.

Concept of steady state stability has been developed to readily evaluate the stability of an equilibrium point from the steady state speed torque curves of the motor and load system. In most of the electrical drives, the electrical time constant of the motor is negligible compared with the mechanical time constant. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient state operation.

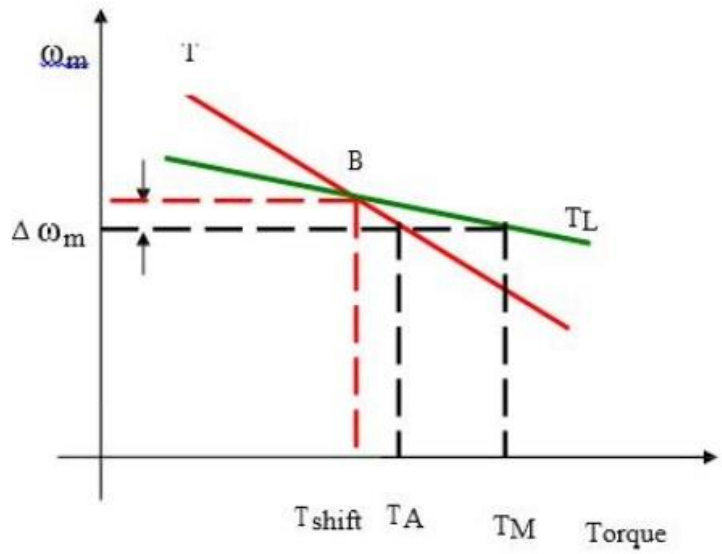
Now, consider the steady state equilibrium point A shown in figure below



Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure.

A decrease in speed causes the load torque to become greater than the motor torque, electric drive decelerates and operating point moves away from point B.

Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B



Basics of Regenerative Braking

In the regenerative braking operation, the motor operates as generator, while it is still connected to the supply. Here, the motor speed is greater than the synchronous speed.

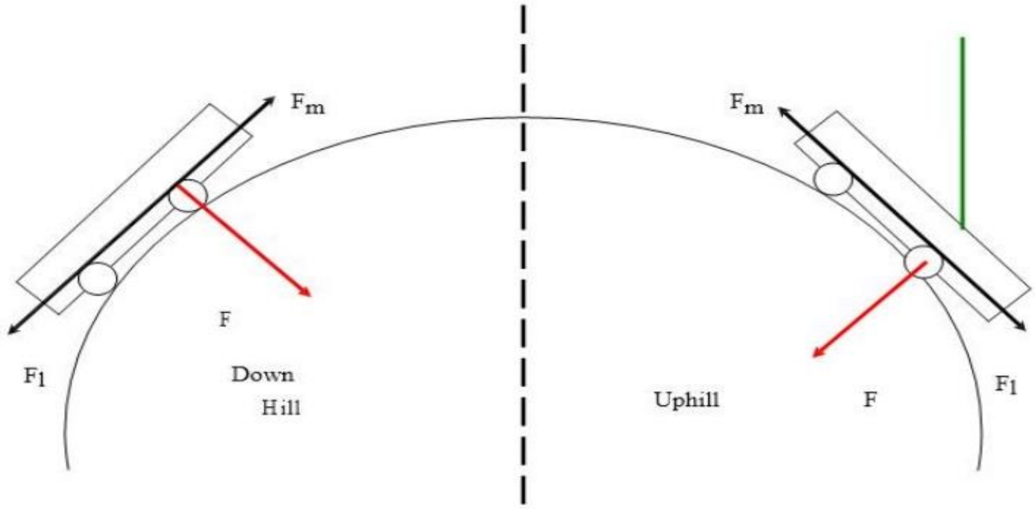
Mechanical energy is converted into electrical energy, part of which is returned to the supply and rest of the energy is last as heat in the winding and bearings of electrical machines pass smoothly from motoring region to generating region, when over driven by the load.

An example of regenerative braking is shown in the figure below. Here an electric motor is driving a trolley bus in the uphill and downhill direction. The gravity force can be resolved into two components in the uphill direction.

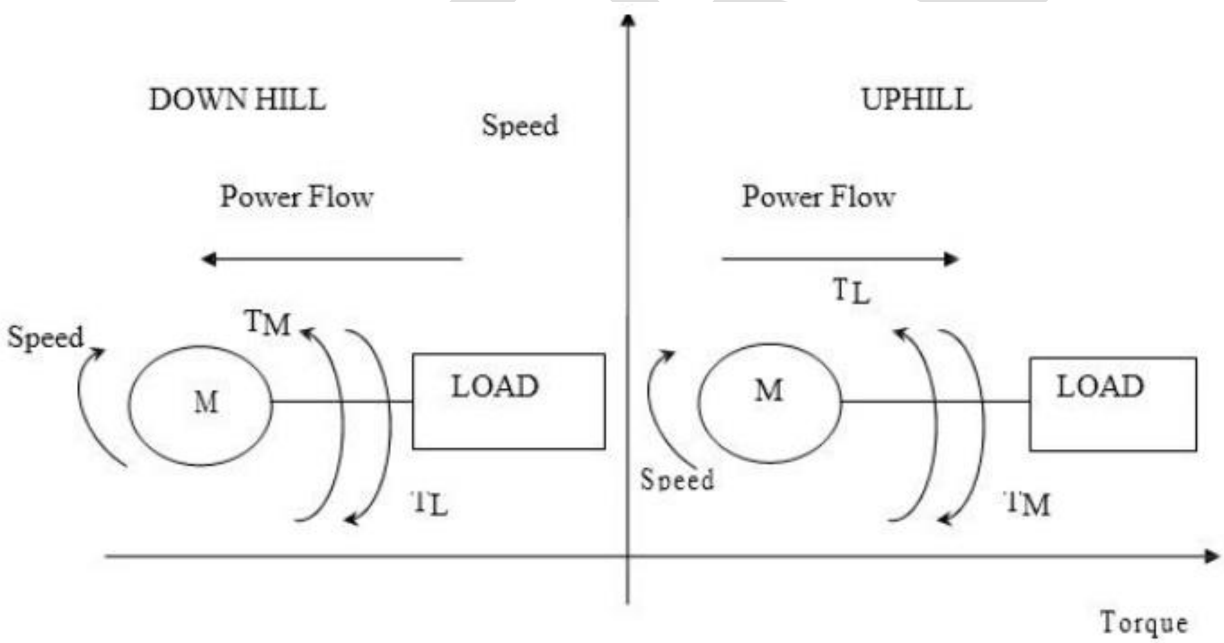
One is perpendicular to the load surface (F) and another one is parallel to the road surface Fl. The parallel force pulls the motor towards bottom of the hill.

If we neglect the rotational losses, the motor must produce force Fm opposite to Fl to move the bus in the uphill direction.

Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power flows from mechanical load to source.



This operation is indicated as shown in the figure below in the first quadrant. Here the power flow is from the motor to load.



Now we consider that the same bus is traveling in down hill, the gravitational force doesn't change its direction but the load torque pushes the motor towards the bottom of the hill. The motor produces a torque in the reverse direction because the direction of the motor torque is always opposite to the direction of the load torque.

Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power flows from mechanical load to source. Hence, the load is driving the machine and the machine is generating electric power that is returned to the supply.

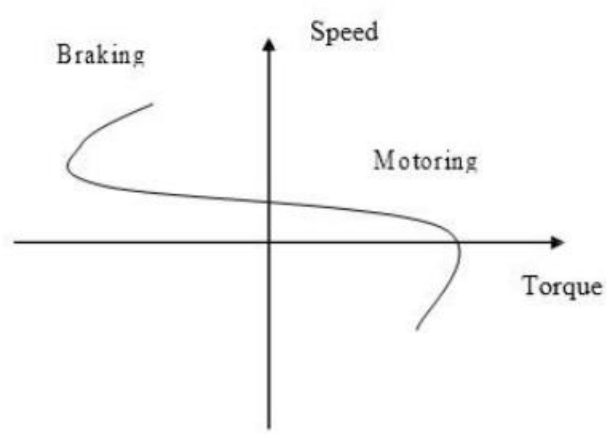
Regenerative braking of Induction motor:

An induction motor is subjected to regenerative braking, if the motor rotates in the same direction as that of the stator magnetic field, but with a speed greater than the synchronous speed. Such a state occurs during any one of the following process.

- Downward motion of a loaded hoisting mechanism
- During flux weakening mode of operation of IM.

Under regenerative braking mode, the machine acts as an induction generator. The induction generator generates electric power and this power is fed back to the supply. This machine takes only the reactive power for excitation.

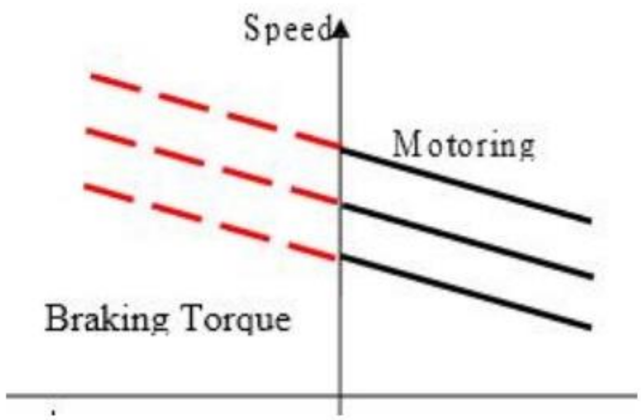
The speed torque characteristic of the motor for regenerative braking is shown in the figure.



Regenerative Braking for DC motor:

In regenerative braking of dc motor, generated energy is supplied to the source. For this the following condition is to be satisfied.

E > V and Ia should be negative



Modes of Operation:

An electrical drive operates in three modes

- Steady state
- Acceleration including Starting
- Deceleration including Stopping

We know that

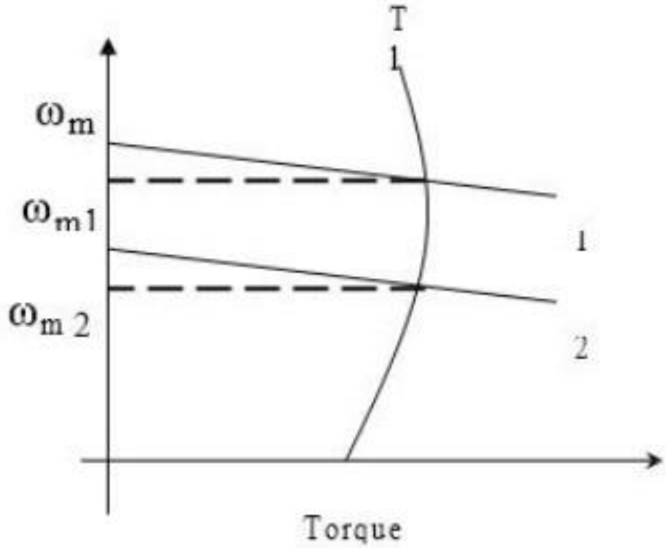
$$T = T1 + J \, d/dt \, (\omega m)$$

According to the above expression the steady state operation takes place when motor torque equals the load torque. The steady state operation for a given speed is realized by adjustment of steady state motor speed torque curve such that the motor and load torques are equal at this speed. Change in speed is achieved by varying the steady state motor speed torque curve so that motor torque equals the load torque at the new desired speed. In the figure shown below when the motor parameters are adjusted to provide speed torque curve 1, drive runs at the desired speed ωm 1 .

Speed is changed to ωm 2 when the motor parameters are adjusted to provide speed torque curve

2. When load torque opposes motion, the motor works as a motor operating in quadrant I or III depending on the direction of rotation. When the load is active it can reverse its sign and act to assist the motion. Steady state operation for such a case can be obtained by adding a mechanical brake which will produce a torque in a direction to oppose the motion. The steady state operation

is obtained at a speed for which braking torque equal the load torque. Drive operates in quadrant II or IV depending upon the rotation.



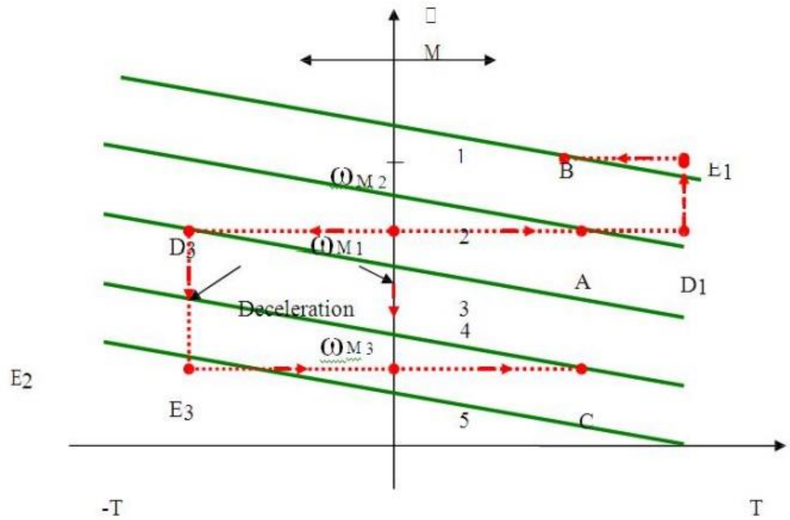
Acceleration and Deceleration modes are transient modes. Drive operates in acceleration mode whenever an increase in its speed is required. For this motor speed torque curve must be changed so that motor torque exceeds the load torque. Time taken for a given change in speed depends on inertia of motor load system and the amount by which motor torque exceeds the load torque.

Increase in motor torque is accompanied by an increase in motor current. Care must be taken to restrict the motor current with in a value which is safe for both motor and power modulator. In applications involving acceleration periods of long duration, current must not be allowed to exceed the rated value. When acceleration periods are of short duration a current higher than the rated value is allowed during acceleration.

In closed loop drives requiring fast response, motor current may be intentionally forced to the maximum value in order to achieve high acceleration. Figure shown below shows the transition from operating point A at speed.

Point B at a higher speedωm 2, when the motor torque is held constant during acceleration. The path consists of AD1E1B. In the figure below, 1 to 5 are motor speed torque curves. Starting is a special case of acceleration where a speed change from 0 to a desired speed takes place. All points mentioned in relation to acceleration are applicable to starting.

The maximum current allowed should not only be safe for motor and power modulator but drop in source voltage caused due to it should also be in acceptable limits. In some applications the motor should accelerate smoothly, without any jerk. This is achieved when the starting torque can be increased step lessly from its zero value. Such a start is known as soft start.



LOAD EQUALISATION IN ELECTRICAL DRIVES

Definition: Load equalisation is the process of smoothing the fluctuating load. The fluctuate load draws heavy current from the supply during the peak interval and also cause a large voltage drop in the system due to which the equipment may get damage. In load equalisation, the energy is stored at light load, and this energy is utilised when the peak load occurs. Thus, the electrical power from the supply remains constant.

The load fluctuation mostly occurs in some of the drives. For example, in a pressing machine, a large torque is required for a short duration. Otherwise, the torque is zero. Some of the other examples are a rolling mill, reciprocating pump, planning machines, electrical hammer, etc.

In electrical drives, the load fluctuation occurs in the wide range. For supplying the peak torque demand to electrical drives the motor should have high ratings, and also the motor will draw pulse current from the supply. The amplitude of pulse current gives rise to a line voltage fluctuation which affected the other load connected to the line.

Method of Load Equalisation

The problem of load fluctuation can be overcome by using the flywheel.The flying wheel is mounted on a motor shaft in non-reversible drives. In variable speed and reversible drive, a flywheel cannot be mounted on the motor shaft as it will increase the transient time of the drive. If the motor is fed from the motor generator set, then flywheel mounted on the motor generator shaft and hence equalises the load on the source but not load on the motor.

When the load is light, the flywheel accelerated and stored the excess energy drawn from the supply. During the peak load, the flying wheel decelerates and supply the stored energy to the load along with the supply energy. Hence the power remains constant, and the load demand is reduced.

Moment of inertia of the flying wheel required for load equalisation is calculated as follows. Consider the linear motor speed torque curve as shown in the figure below.

$$\omega_m = \omega_{m0} - \frac{\omega_{m0} - \omega_{mr}}{T_r} \times T \ldots\ldots\ldots\ldots equ(1)$$

Assumed the response of the motor is slow due to large inertia and hence applicable for transient operation. Differentiate the equation (1) and multiply both sides by J (moment of inertia).

$$J\frac{d_{\omega m}}{dt} = \frac{J(\omega_{m0} - \omega_{mr})}{T_r}\frac{dT}{dt} \ldots\ldots\ldots\ldots equ(2)$$

$$J\frac{d_{\omega m}}{dt} = -T_m\frac{dT}{dt} \ldots\ldots\ldots\ldots equ(3)$$

$$T_m = \frac{(\omega_{m0} - \omega_{mr})}{T_r} \ldots\ldots\ldots\ldots\ldots\ldots equ(4)$$

Where T_m is the mechanical time constant of the motor. It is the time required for the motor speed to change by ($\omega_{m0} - \omega_m$) when motor torque is maintained constant at rated value τ_r. From equation(2) and (3)

$$T_m\frac{dT}{dt} + T = T_l \ldots\ldots\ldots equ(5)$$

Consider a periodic load torque a cycle which consists of one high load period with torque T_{lh} and duration the, and one light load period with torque T_{ll} and duration t_l

$$T = T_{lh}\left(1 - e^{-t/\tau_m}\right) + T_{max}e^{-t/\tau_m} \ldots\ldots equ(6)$$

$$for\ 0 \le t \le t_h$$

Where T_{min} is the motor torque at t = 0 which is also the instant when heavy load T_{lh} is applied. If motor torque at the end of heavy load period is T_{max}, then from the equation (6)

$$T_{max} = T_{lh}\left(1 - e^{-t/\tau_m}\right) + T_{max}e^{-t/\tau_m} \ldots\ldots equ(7)$$

Solution of equation (5) for the light load period with the initial motor torque equal to T_{max} is

$$T = T_{ll}\left(1 - e^{-t/\tau_m}\right) + T_{max}e^{-t/\tau_m} \ldots\ldots equ(8)$$

$$for\ 0 \le t' \le t_h$$

where $t' = t - t_h$

When operating at steady state the motor torque at the end of a cycle will be the same as at the beginning of a cycle.Hence at $t' = t_l$, $T = t_{min}$. Substituting in equation (8) give

$$T_{min} = T_{ll}\left(1 - e^{-t/\tau_m}\right) + T_{max}e^{-t/\tau_m} \ldots\ldots equ(9)$$

From equation (7)

$$\tau_m = \frac{t_h}{log_e\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \ldots\ldots\ldots\ldots equ(10)$$

From equation (4) and (10)

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})} \times \frac{t_h}{log_e\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \ldots\ldots\ldots\ldots equ(11)$$

Also from equation (9)

$$\tau_m = \frac{t_1}{log_e\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \ldots\ldots\ldots\ldots equ(12)$$

From equation (4) and (11)

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})} \times \frac{t_1}{log_e\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \ldots\ldots\ldots\ldots..equ(13)$$

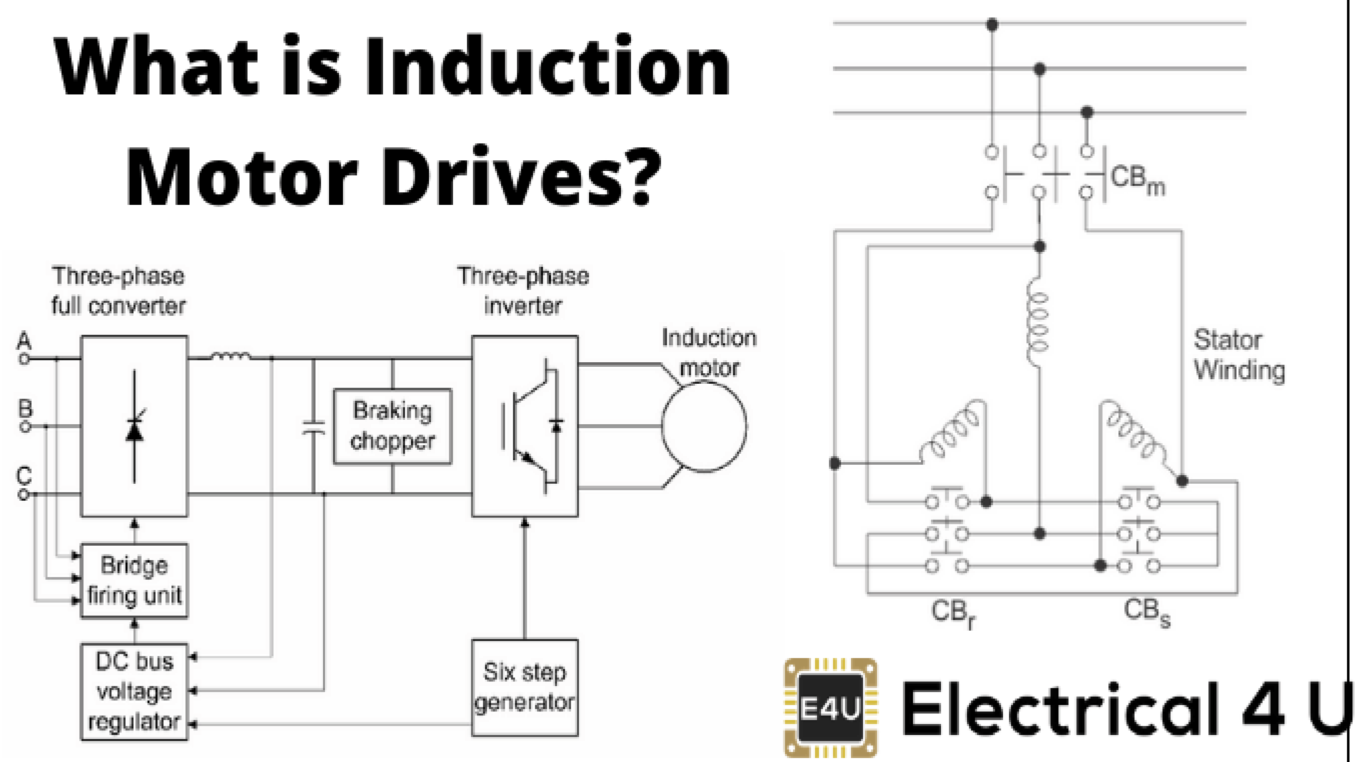
Moment of inertia of the flywheel required can be calculated either from equation(11) and (12)

$$J = WR^2, kg - m^2 \ldots\ldots\ldots\ldots equ(14)$$

Where W is the weight of the wheel (Kg), and R is the radius (m).

Note: The moment of inertia is the angular obstruction of the rotating body. It is the product of the mass and a square of a distance from the axis of rotation.

INDUCTION MOTOR DRIVES | STARTING BRAKING SPEED CONTROL OF INDUCTION MOTOR



Before discussing, **induction motor drives** it's important to understand and know about induction motors. In very simple words induction motors can be described as a three-phase, self-starting constant speed AC motors. The reason for describing induction motors as constant speed is because normally these motors have a constant speed depending on the frequency of the supply and the number of windings.

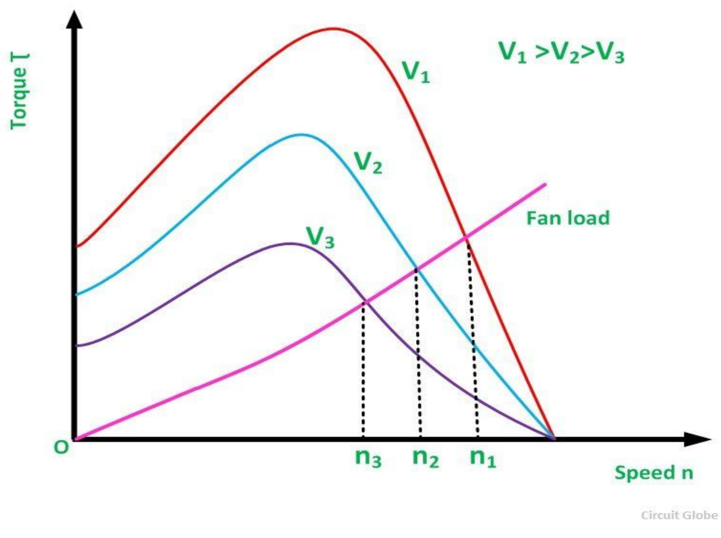
In the past, it was not possible to control the speed of the induction motors according to one's needs. That's why their use was limited and despite having many other advantages over DC motors they could not be used because of this disadvantage. But at the field of drivers have improved due to the availability of thyristors or SCRs, power transistors, IGBTs, and GTOs the variable speed **induction motor drives** have been invented.

Though the cost of these drivers is more than DC driver, still the use of induction motors is increasing and they are replacing DC motors because of their advantages. While discussing this topic we will look through the starting, braking and speed control of induction motors.

STATOR VOLTAGE CONTROL OF AN INDUCTION MOTOR

Stator Voltage Control is a method used to control the speed of an **Induction Motor.** The speed of a three phase induction motor can be varied by varying the supply voltage. As we already know that the torque developed is proportional to the square of the supply voltage and the slip at the maximum torque is independent of the supply voltage. The variation in the supply voltage does not alter the synchronous speed of the motor.

The **Torque-Speed Characteristics** of the three phase Induction motors for varying supply voltage and also for the fan load are shown below.



By varying the **supplying voltage**, the speed can be controlled. The voltage is varied until the torque required by the load is developed, at the desired speed. The torque developed is proportional to the square of the supply voltage and the current is proportional to the voltage.

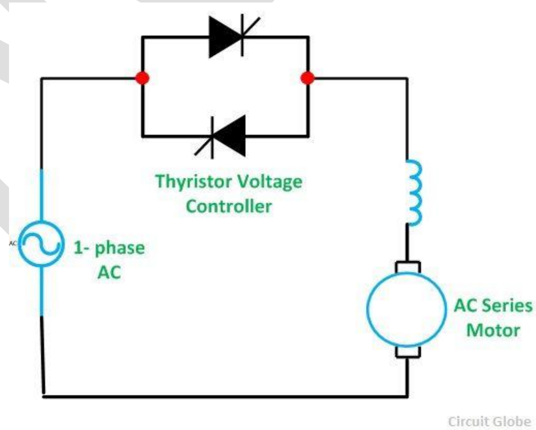
Hence, to reduce the speed for the same value of the same current, the value of the voltage is reduced and as a result, the torque developed by the motor is reduced. This stator voltage control method is suitable for the applications where the load torque decreases with the speed. **For example-** In the fan load.

This method gives a **speed control** only below the normal rated speed as the operation of the voltages if higher than the rated voltage is not admissible. This method is suitable where the intermittent operation of the drive is required and also for the fan and pump drives. As in fan and pump the load torque varies as the square of the speed. These types of drives required low torque at lower speeds. This condition can be obtained by applying lower voltage without exceeding the motor current.

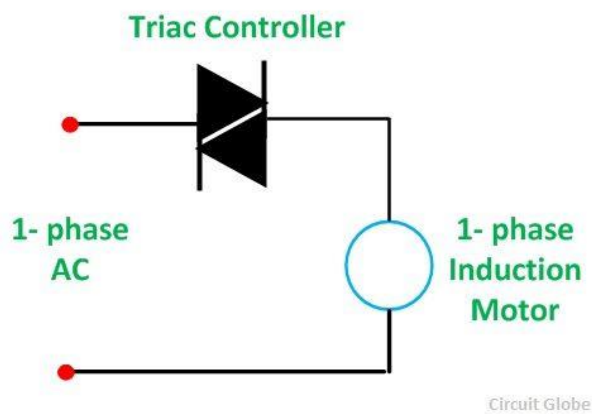
The variable voltage for speed control of small size motors mainly for single phase can be obtained by the following methods given below.

- By connecting an external resistance in the stator circuit of the motor.
- By using an Auto transformer.
- By using a Thyristor voltage controller
- By using a Triac Controller

Nowadays the **Thyristor voltage controller** method is preferred for varying the voltage. For a single phase supply, two Thyristors are connected back to back as shown in the figure below.

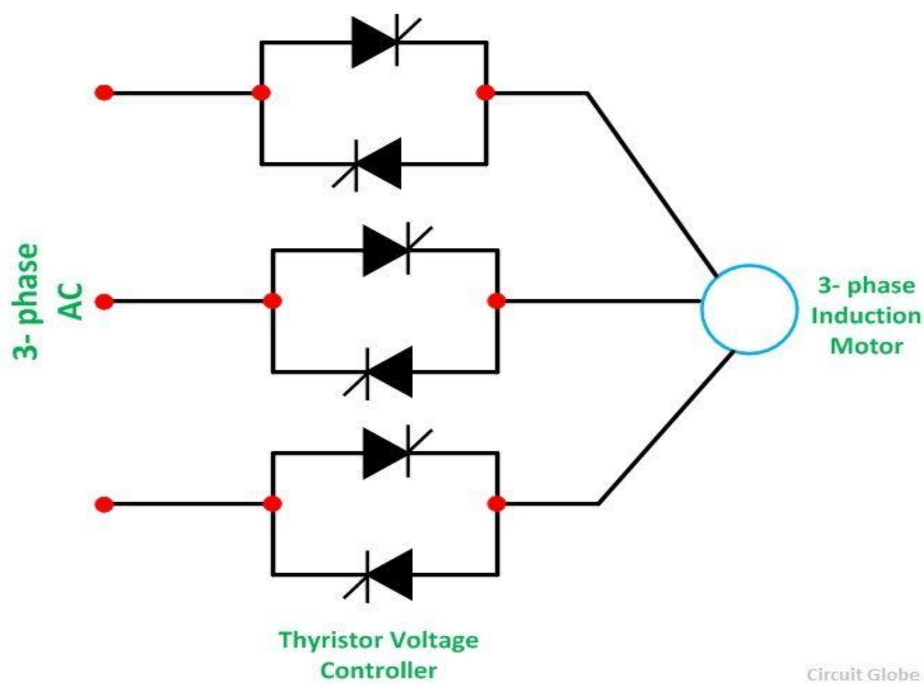


The domestic fan motors, which are single phase are controlled by a single phase **Triac Voltage Controller** as shown in the figure below.



Speed control is obtained by varying the firing angle of the **Triac**. These controllers are known as **Solid State fan regulators**. As the solid state regulators are more compact and efficient as compared to the conventional variable regulator. Thus, they are preferred over the normal regulator.

In case of a three phase induction, motor three pairs of Thyristor are required which are connected back to back. Each pair consists of two Thyristor. The diagram below shows the **Stator Voltage Control** of the three phase induction motors by **Thyristor Voltage Controller.**

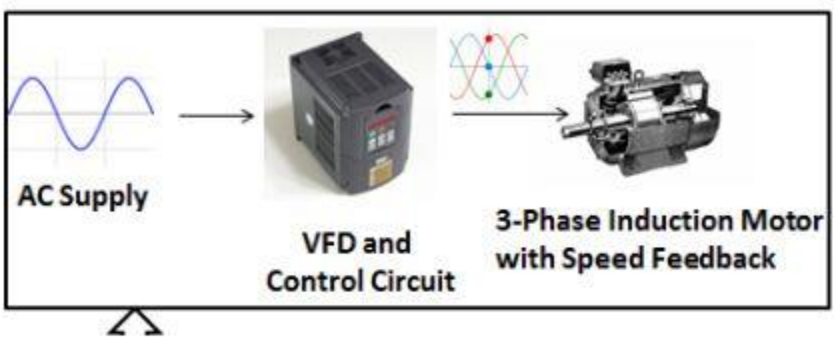


Each pair of the Thyristor controls the voltage of the phase to which it is connected. Speed control is obtained by varying the conduction period of the Thyristor. For lower power ratings, the back to back Thyristor pairs connected in each phase is replaced by Traic.

VARIABLE FREQUENCY CONTROL METHOD

Variable Frequency drive or VFD is the most popular and has found widespread use in industrial and domestic applications because of its ease of implementation. They can be used in control of motors used in conveyors and other machinery. In Industries Variable Frequency Drive (VFD) is an integral part due to its versatility. Internal architecture of any VFD consist of several power electronics circuits (component) and are interfaced to each other which makes this architecture an interesting application of Power Electronics Engineering.

Block Diagram:



VFD Block Diagram

Variable Frequency Drive (VFD), also known as Variable Speed drive, Micro Drive, or AC drive, is an electronic device that varies the frequency and the speed of AC motors as per the requirements of the loads.

Theory

Sinusoidal Pulse Width Modulation(SPWM) is a scheme of modulation useful for applying Sinusoidal 3 phase voltage to a 3 phase load like 3 phase Induction Motor.

We assume that the 3 phase Inverter circuit is powered by a constant DC voltage source provided by the DC link Capacitor. The output voltage is varied by changing the switching sequence of the IGBT switches as shown in the figure below.

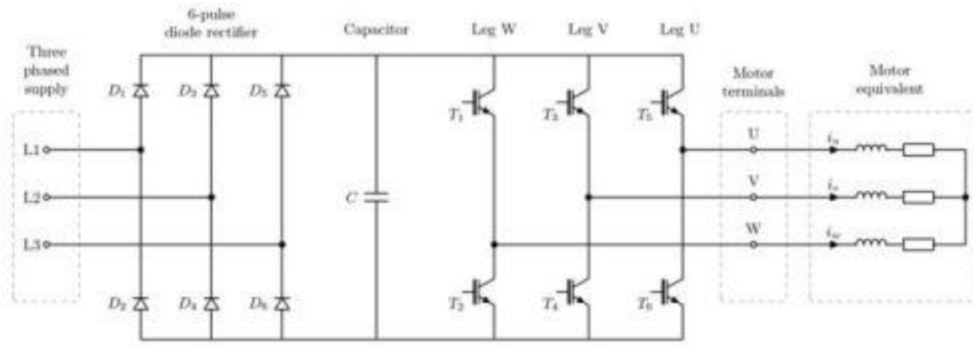


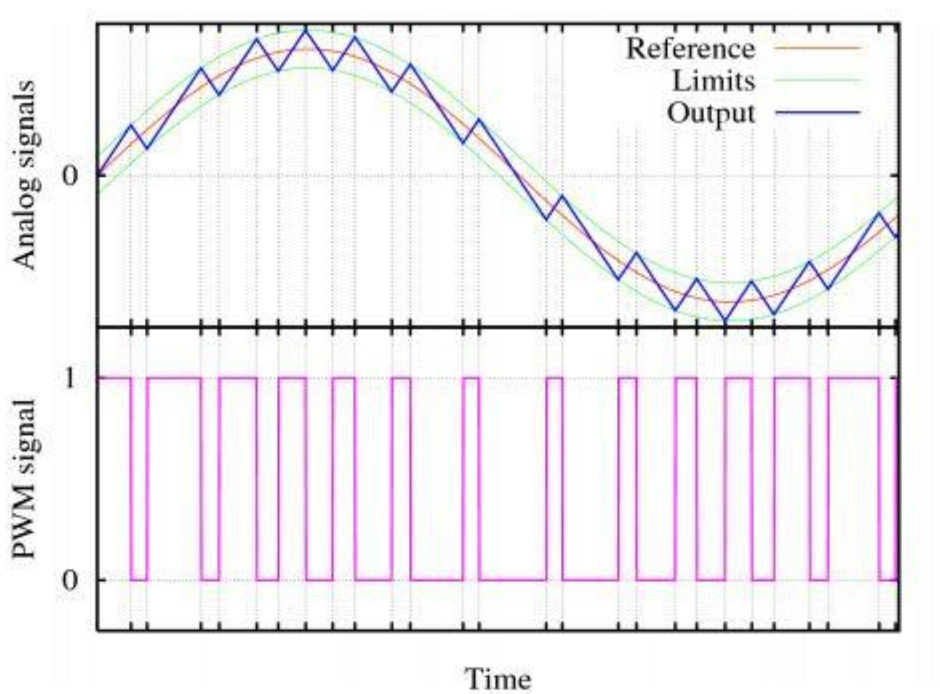
Figure 3.1: Schematic representation of the Rectifier and Inverter Circuit.

Inverter circuit

There challenges that are faced are:

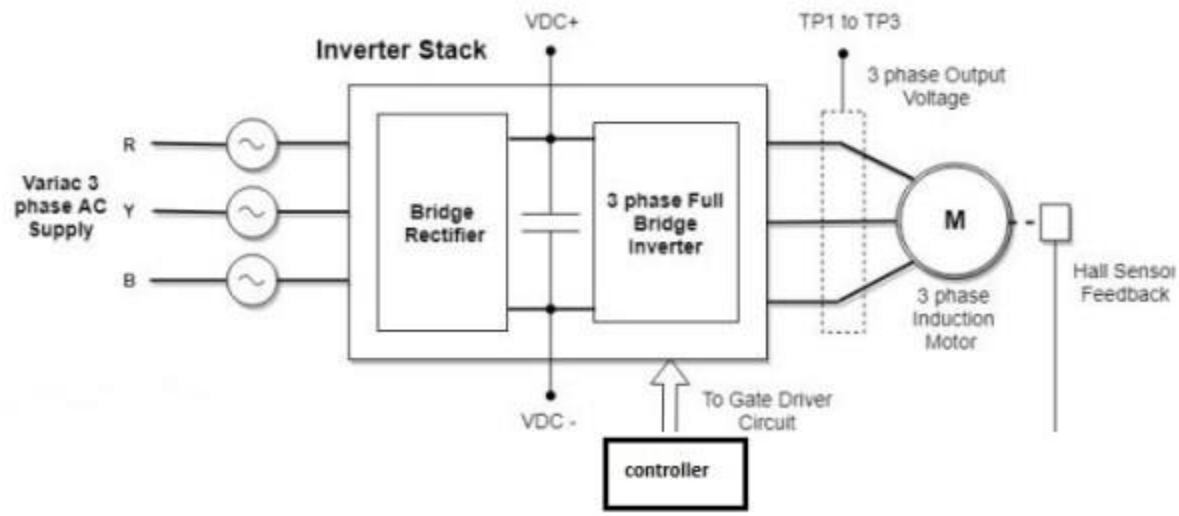
• DC link capacitor is the only source of DC voltage that is assumed to be constant which is a challenge.

• The six pulses generated by the controller should be applied to the IGBT gates by means of driver circuits and there should be no overlaps causing any sort of short circuit.



PWM and Sine Wave

Sinusoidal pulse width modulation is generation method useful in Inverters. The Inverter produces AC Voltage that is only possible when the IGBT's are fired by means of some modulation technique. The IGBT gate pulses are generated by means of a control algorithm from a ***controller*** and are provided as an input to the gate driver circuit which supplies with the enough current. The pulse width generated in produced using sine table and its approximated view is a sine wave as shown in the figure. With sinusoidal or sine weighted pulse width modulation, several pulses are produced per half cycle. The pulse at the center are wide while at the ends of the half cycle are narrow. To change the output frequency of the sine wave, the frequency of generated SPWM signal need to be changed.



Detailed VFD

Level Shifter

level shifter

IGBT gate driver circuit is present inside the power module which drives the current capability of the pulses. Pulses generated by DSP are of 3.3V (CMOS level signal), thus to convert them to 15V, external hex converter IC CD4504 is used.It is also called as level Shifter.

3 phase induction motor

The three phase Induction motor has the following Specifications:

• Power Rating : 0.37 kW or 0.5 HP

• Voltage Rating : 220V

• Current Rating : 2A

• Maximum Speed(N) : 1400RPM

DSP to generate igbt gate pulses.

c2000 dsp

- The F2802x Piccolo family of micro-controllers provides the power of the C28x core coupled with highly integrated control peripherals in low pin-count devices. This family is code-compatible with previous C28x-based code, and also provides a high level of analog integration.
- An internal voltage regulator allows for single-rail operation. Enhancements have been made to the HRPWM to allow for dual-edge control (frequency modulation).
- Analog comparators with internal 10-bit references have been added and can be routed directly to control the PWM outputs. The ADC converts from 0 to 3.3-V fixed full-scale range and supports ratio-metric references.
- The ADC interface has been optimized for low overhead and latency. The use of the DSP is to provide SVM(Space Vector Modulation) equivalent pulses for the Inverter circuit using SVM algorithm embed inside the processor using Code Composer Studio platform.
- Another uses is to adjust the SVM pulse frequency using analog potentiometer interfaced to the ADC of the C2000 DSP processor

APPENDIX I
CONTENT BEYOND THE SYLLABUS

APPENDIX I

What is Electric Traction System?

A system which causes the propulsion of vehicle in which tractive or driving force is obtained from various devices such as diesel engine drives, steam engine drives, electric motors, etc. is called as traction system.

It can also be defined as the railway vehicle that provides the necessary traction power to move the train is referred as the traction or locomotive. This traction power can be diesel, steam or electric power.

The traction system can be classified as non-electric and electric traction systems.

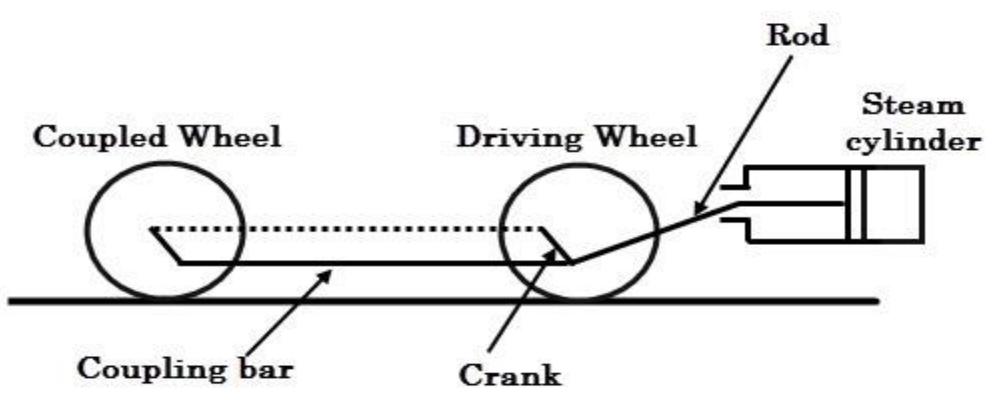
Non-electric traction system

A traction system that doesn't use electrical energy for the movement of vehicle at any stage is referred as non-electric traction system.

The steam engine drive is the best example of a non electric traction system and it is the first locomotive system used before the invention of actual electric traction systems.

The steam locomotive system uses the superheated steam to produce mechanical energy for the movement of vehicle.

This may use coal or petroleum as fuel, liberates thermal energy to produce the steam pressure and then it is converted into kinetic energy so that mechanical movement of the vehicle is produced.



The disadvantages of steam locomotive systems , such as , low fuel efficiency, poor technical performance, maintenance of a large number of water supply facilities, and high maintenance cost makes them to be replaced by alternative traction systems and hence the electric traction.

The following are the two types of non electric traction systems.

- Steam engine drive based vehicles (used for railways)
- Internal combustion (IC) engine drive based vehicles (used for road transport)

Electric traction system

Electric traction involves the use of electricity at some stage or all the stages of locomotive movement. This system includes straight electrical drive, diesel electric drive and battery operated electric drive vehicles.

In this, electrical motors are used for producing the vehicle movement and are powered by drawing electricity from utilities or diesel generators or batteries.

It has many advantages over non-electric traction systems such as more clean and easy to handle, no need of coal and water, easy speed control, high efficiency, low maintenance and running costs, etc.

As mentioned above, electric traction systems can be self contained locomotives or vehicles that receive power from electric distribution system (substations). Self contained locomotives includes

- Battery operated electrical drives
- Diesel operated electrical drives

Vehicles that receives the power from substation is also referred as a third rail systems which includes

- Railway electric vehicles fed from overhead AC or DC supply
- Trolley buses or tramways supplied with DC supply (i.e., battery electric drives)

4 Supply Systems of Electric Traction

The way of giving the power supply to locomotive unit is generally referred as traction electrification system. Presently, there are four types of track electrification systems are available based on the availability of supply. These are

- DC traction system
- Single phase AC traction system

- Three phase AC traction system
- Composite traction system

DC Traction System

In this traction system, electrical motors are operates on DC supply to produce necessary movement of the vehicle. Mostly DC series motors are used in this system. For trolley buses and tramways, DC compound motors are used where regenerative braking is required.

The various operating voltages of DC traction system include 600V, 750 V, 1500V and 3000V.

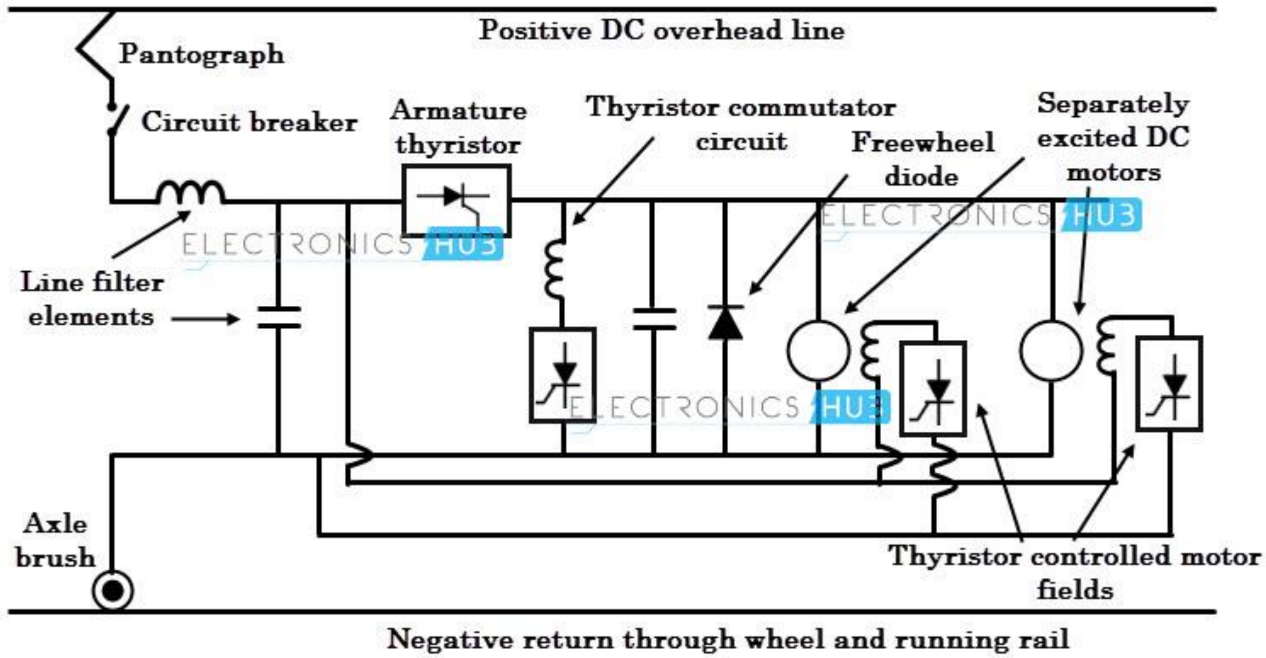
- DC supply at 600-750V is universally employed for tramways and light metros in urban areas and for many suburban areas. This supply is obtained from a third rail or conductor rail, which involves very large currents.
- DC supply at 1500- 3000 is used for main line services such as light and heavy metros. This supply is drawn mostly from an overhead line system that involves small currents.

In both cases, only one conductor or rail is required to supply power to locomotive while track rails are used as return conductors in majority of cases.

Both these supply voltages are fed from substations which are located 3-5 KM for suburban services and 40 to 50KMs for main line services. These substations receive power (typically, 110/132 KV, 3 phase) from electric power grids.

This three phase high voltage is stepped-down and converted into single phase low voltage using scott-connected three phase transformers.

This single phase low voltage is then converted into DC voltage using suitable converters or rectifier such as power electronic converter, rotary converters, mercury arc converters, etc. The DC supply is then applied to the DC motor via suitable contact system and additional circuitry.



The advantages of this system include

- In case of heavy trains that require frequent and rapid accelerations, DC traction motors are better choice as compared AC motors.
- DC train consumes less energy compared to AC unit for operating same service conditions.
- The equipment in DC traction system is less costly, lighter and more efficient than AC traction system.
- It causes no electrical interference with nearby communication lines.

Despite all these advantages, DC electrical system necessitates AC to DC conversion substations relatively at very short distances. This is the main disadvantage of DC traction system.

That's why this system is preferred only for suburban and road transport services wherein stops are frequent and also distance between stops is small.

Single Phase AC Traction System

In this type of traction system, AC series motors are used to produce the propulsion of vehicle. This system uses AC voltages from 15-25KV at a frequency of 16.7 (i.e., 16 2/3) or 25 Hz. This low frequency leads to give better performance and more efficient operation by the series motor.

This single phase supply is fed to the locomotive unit via a single overhead line while track provides the return path.

The high voltages (15-25KV) obtained from overhead conductor are stepped down to a suitable motor operating range (typically 300-400V range) using step-down transformer carried by the locomotive unit itself.

The secondary tapping of this transformer offer variable voltage to AC series motor for speed regulation.

The low frequency operation of overhead line reduces the communication interferences. Also, the reactance of the line is low at lower frequency and hence the voltage drop in the line is reduced.

Because of this low line voltage drop, it is feasible to locate the substations at 50 to 80kms apart from each other. Therefore, this system is preferred for main line services where cost of overhead system is not a much important factor and for suburban services where rapid acceleration and retardation are not required.

Three Phase AC Traction System

In this, three phase induction motors are used for the movement of locomotive. This system normally works on 3000-3600V AC at a frequency either 16 2/3 or normal supply frequency.

This system employs two overhead lines for two phases, whereas the track forms third phase. These conductors are powered from substations which are rated at higher voltages and they receive power from three-phase transmission lines.

The high voltages from transmission lines are stepped down to 3.3 KV (3000-3600 V) by transformers while the frequency is reduced by frequency converters installed at substations.

The three phase induction motor used in this system has the following characteristics; simple and robust construction, provision of regenerative braking without additional equipment and high operating efficiency, better performance, etc.

However, these motors are suffer with some drawbacks such as high starting current, low starting torque, complicated overhead structure, especially at crossings and junctions and not suitable constant speed characteristics of induction motor traction work.

These systems are adopted where high output power is required and also where automatic regeneration braking is needed. However, these systems do not found much favour compared to other systems.

Composite Traction System

The above discussed methods have their own merits and demerits. Single phase AC system has less distribution cost whereas DC system has excellent driving capability by DC series motors and three phase system has automatic regenerative braking capacity.

So by combining the advantages of AC/DC and single/three phase systems, the overall performance of the traction system gives better result than individual system and hence the evolution of composite system.

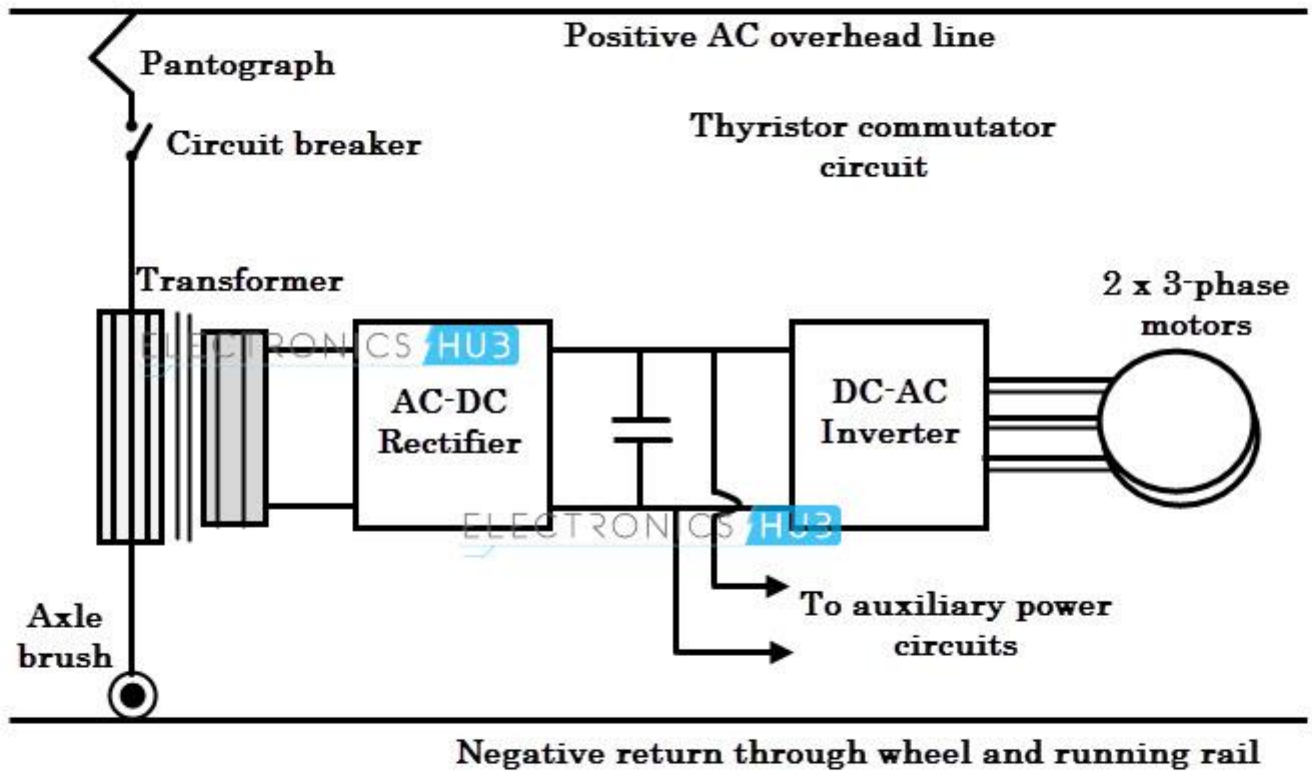
Basically composite systems are of two types, namely

- Single phase to three phase system
- Single phase to DC system

Single phase to three phase system

This traction system is also called Kando system. It consists of single phase16KV, 50 Hz supply which is fed from the substation and is being carried through a single overhead conductor.

The single phase supply is then converted into three phase supply of the same frequency using phase converter equipment in the locomotive itself. The three phase supply is then fed to induction motors to drive the locomotive.



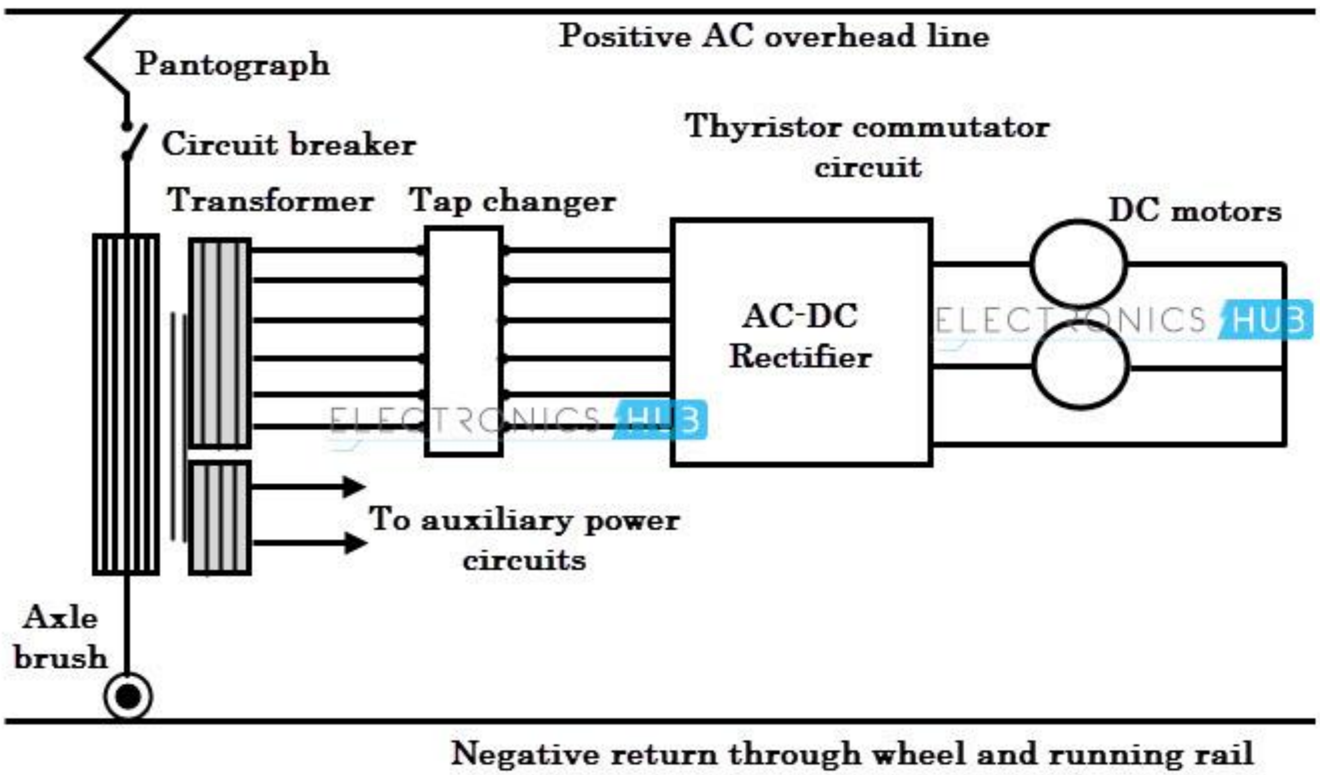
It is also possible to develop high starting torque of induction motors by reducing the supply frequency at ½ to 9 Hz by means of inverter controlled through silicon controlled rectifiers.

The main advantage of this system is that the overhead two conductor arrangement of three phase AC system is reduced to a single overhead conductor and hence more economical.

Single phase to DC system

This traction system is most popular and widely used system everywhere. It combines the single phase high voltage AC distribution at industrial frequency with DC series motor traction.

In this, the overhead line carries single phase, 25KV, 50 Hz supply which is then stepped down to a desired range using step-down transformer located in the locomotive unit itself.



This single phase supply is then converted into DC using rectifier (in the locomotive) and then applied to DC series motor.

The advantages of this system include higher starting efficiency, less number of substations, simple substation design and lower cost of fixed installations.

Main Parts of AC Electric Locomotive

The figure below shows the block diagram of an AC locomotive system that employs single phase supply to drive three phase motor.

The various components of this system include overhead contact wire, circuit breakers, pantograph, transformer, three phase traction motor, rectifier, inverter, smoothing reactor, etc.

Pantograph

The main function of pantograph is to maintain link between overhead conductor and power circuit of locomotive at different speeds of the vehicle under all wind conditions. It collects the current from overhead conductor and supplies to rest circuit.

Circuit Breaker

It protects the power circuit in the event of any fault by isolating it from the supply. It also isolates the circuit during maintenance.

Transformer

It receives the high voltage from overhead conductor via pantograph and circuit breaker and then step-down the voltage to desired level required by the rest circuit.

Rectifier

It converts a low voltage AC supply from the secondary of transformer to a DC supply.

DC Link

It connects the rectifier and inverter circuits. It consists of filter arrangement (capacitor and inductor arrangement) that filters the output from rectifier (by removing the harmonics form it) and then supplies it to the inverter.

Main Inverter

It converts the DC power to three phase AC power in order to drive three phase AC motors.

Axle Brush

It acts as a return path for the supply. Once the power is drawn to the locomotive from overhead system, the current complete its path through axle brush and one of running tacks.

Auxiliary Inverter

This inverter supplies the power to other parts in the locomotive unit including fans, motor blowers, compressors, etc.

Battery

It supplies the necessary starting current and also power up the essential circuits such as emergency lighting.

Compressor

It maintains the cooling/heating requirement in the locomotive unit.

Cooling Fans

These fans maintain the necessary cooling for the power circuits. Modern locomotive systems use electronically controlled air management systems to keep the desired temperature.