LECTURE NOTES

ON

BASIC ELETRICAL ENGINEERING(BEE)

ACADEMIC YEAR 2021-22

I B.Tech.–II SEMESTER for ECE
(R20)

DEPARTMENT OF HUMANITIES AND BASIC SCIENCES

V S M COLLEGE OF ENGINEERING
RAMCHANDRAPURAM
E.G DISTRICT
533255

VSM COLLEGE OF ENGINEERING
RAMACHANDRAPURAM

BEE syllabus

Unit I
DC Machines
Principle of operation of DC generator – emf equation – types of DC machines – torque equation of DC motor – applications – three point starter - losses and efficiency - swinburne's test - speed control methods – OCC of DC generator- Brake test on DC Shunt motor-numerical problems

Unit II
Transformers
Principle of operation of single phase transformer constructional features – EMF equation – Losses and efficiency of transformer- regulation of transformer – OC & SC tests predetermination of efficiency and regulations – Sumpner's test- Numerical Problems.

Unit III
Synchronous Generators
Principle of operation and construction of alternators – types of alternators Regulation of alternator by synchronous impedance method-EMF equation of three phase alternator

Synchronous Motors
Construction of three phase synchronous motor - operating principle –equivalent circuit of synchronous motor.

Unit IV
Induction Machine: Principle of operation and construction of three-phase induction motors – slip ring and squirrel cage motors – slip-torque characteristics – efficiency calculation – starting methods-Brake test on 3-Phase Induction Motor.

Unit V **Special Machines:** Principle of operation and construction - single phase induction motor - shaded pole motors – capacitor motors and AC servomotor

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DEPARTMENT OF BASIC SCIENCES AND HUMANITIES

Course Title	Year/Sem	Branch	Periods per Week
BASIC ELECTRICAL ENGINEERING	1/11	ECE BRANCH	5

Course Outcomes:

- understand social or transactional dialogues spoken by native speakers of English andidentify the context, topic, and pieces of specific information
- ask and answer general questions on familiar topics and introduce oneself/others
- employ suitable strategies for skimming and scanning to get the general idea of a textand locate specific information
- recognize paragraph structure and be able to match beginnings/endings/headings with paragraphs
- form sentences using proper grammatical structures and correct word forms

Unit No	Outcomes	Name of the Topic	No. of Periods required	Total Periods	Reference Book	Methodology to be adopted
		Unit-1				
I	CO 1, CO2, CO3, CO4 DC Machines	Principle of operation of DC generator	1	15	T1, T2 R20	Black Board
		emf equation	2			Black Board
		types of DC machines	1			Black Board
		torque equation of DC motor	1			Black Board
		applications	1			Black Board
		– three point starter	1			Black Board
		- losses and efficiency -	2			Black Board
		swinburne's test -	1			
		speed control methods	1			Black Board
		OCC of DC generator	1			Black Board
		Brake test on DC Shunt moto	1			Black Board
		numerical problems	2			Black Board

		Unit-2				
II	CO 1, CO2, CO3, CO4 Transformers	Principle of operation of single phase transformer constructional features	2	12	T1, T2 R20	Black Board
		EMF equation	2			Black Board
		Losses and efficiency of transformer	2			Black Board
		- regulation of transformer	2			Black Board
		OC & SC tests predetermination of efficiency and regulations	2			Black Board
		Sumpner's test-NumericalProblems.	2			Black Board
		Unit-3				
III	CO 1, CO2, CO3, CO4 Synchronous Generators AND Synchronous Motors	Principle of operation and construction of alternators	2	12	T1, T2 R20	Black Board
		types of alternators Regulation of alternator by synchronous impedance method	2			Black Board
		types of alternators Regulation of alternator by synchronous impedance method	2			Black Board
		Construction of three phase synchronous moto	2			Black Board
		operating principle	2			
		equivalent circuit of synchronous motor	2			Black Board

	CO 1, CO2, CO3, CO4	**Unit-4**				
		Principle of operation and construction of three-phase induction motors	2			Black Board
		slip ring and squirrel cage motors	2			Black Board
		slip-torque characteristics	2			Black Board
		efficiency calculation	2			Black Board
		starting methods	2			Black Board
	Induction Machine	Brake test on 3-Phase Induction Motor	2	12		Black Board

	CO 1, CO2, CO3, CO4 Special Machines:	**Unit-5**				
		Principle of operation and construction	2			Black Board
		- single phase induction motor	2			Black Board
		shaded pole motors –	2			E-Classroom
V		capacitor motors and AC servomotor	2	08	T1, T2 R20	Black Board

Prescribed text books for theory for Semester-I:

“**Infotech English**”, Maruthi Publications. (Detailed)

“**The Individual Society”,** Pearson Publications.(Non-detailed)

Prescribed text book for Laboratory for Semester-I:

1. “**Infotech English**”, Maruthi Publications. (with Compact Disc)

Reference Books:

Bailey, Stephen. *Academic writing: A handbook for international students*. Routledge, 2014.

Chase, Becky Tarver. *Pathways: Listening, Speaking and Critical Thinking.* Heinley ELT;2ndEdition, 2018.

Skillful Level 2 Reading & Writing Student's Book Pack (B1) Macmillan Educational.

Hewings, Martin. *Cambridge Academic English (B2)*. CUP, 2012.

Faculty Member **Head of the Department** **Principal**

Unit – 1 (BEE) R19& R20 Regulations – I ECE II Semester

DC Machines: Principle of operation of DC generator – emf equation – types of DC machines – torque equation of DC motor – applications – three point starter - losses and efficiency - Swinburne's test - speed control methods – OCC of DC generator- Brake test on DC Shunt motor-numerical problems

PRINCIPLE OF OPERATION OF DC GENERATOR

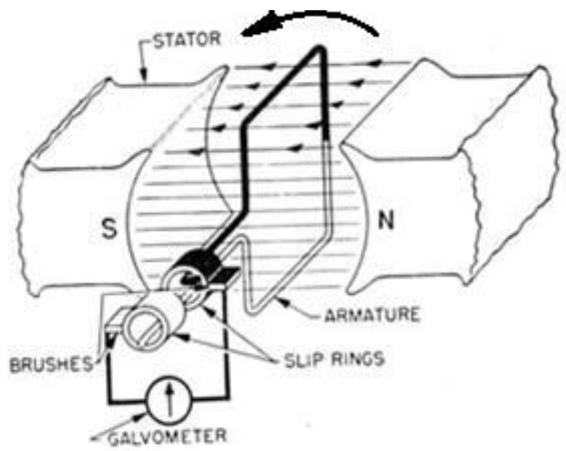
1. DC Generator is an electro mechanical energy conversion device used to ***convert mechanical energy to electrical energy.***
2. It works as per ***Faradays laws of electromagnetic induction*** which states that

> I Law: *"Whenever the conductor cuts the magnetic flux a dynamical emf is induced in the conductor"*
> II Law: *"The magnitude of the emf induced is directly proportional to the rate of change of flux linkages"*

3. ***Fleming's right hand rule*** is used to obtain the direction of the current in the coil of the DC Generator.

Simple loop dc generator:

The simple loop dc generator is assumed to have the following parts as shown in Fig (a)

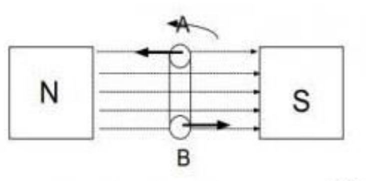


- Two permanent magnets (North pole and South pole) as stator
- A single turn rectangular coil named as Armature (placed on the shaft) as rotor
- Two Slip rings rotating along with the armature coil
- Two static carbon brushes mounted on the slip rings
- External load or galvanometer

The rectangular shaped armature coil is assumed to be rotated in anticlockwise with an angular velocity of ω rad/sec.

The working operation of the simple loop generator is explained over one complete rotation of the coil for 360^0 and is shown in the below figure at different positions of the coil.

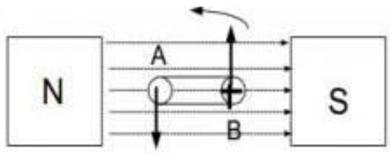
<u>At 0 degrees Position (1):</u>



Position 1: $(\theta = 0^{o})$minimum $\frac{d\emptyset}{dt}$

1. This position is also known as the "Neutral Plane";
2. In this position the loop is parallel to the magnetic lines of flux
3. In this position there is maximum flux passing through the coil.
4. No EMF is induced in the coil because of no "Change in flux through the loop".

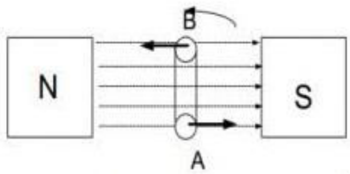
<u>At 90 degrees Position (2):</u>



Position 2: $(\theta = 90^{o})$ maximum$\frac{d\emptyset}{dt}$

1. After the loop has been rotated 90 degrees clockwise through the magnetic field the flux linkage through it now becomes zero.
2. But the rate of change of flux through it was maximum,
3. This results in an induced EMF which climbs from zero to its peak value.

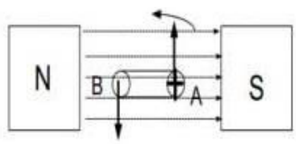
<u>At 180 degrees Position (3):</u>



Position 3: $(\theta = 180^{o})$minimum $\frac{d\emptyset}{dt}$

1. Once again the coil is rotated 90 degrees clockwise resulting in the completion of a 180 degrees cycle.
2. Here the loop is perpendicular to the magnetic lines of force
3. This means that there is maximum flux density through it resulting the EMF to falls back to zero.

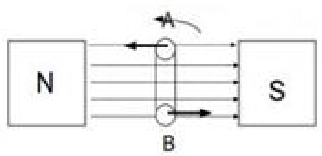
<u>At 270 degrees Position (4):</u>



Position 4: $(\theta = 270^{o})$ maximum$\frac{d\emptyset}{dt}$

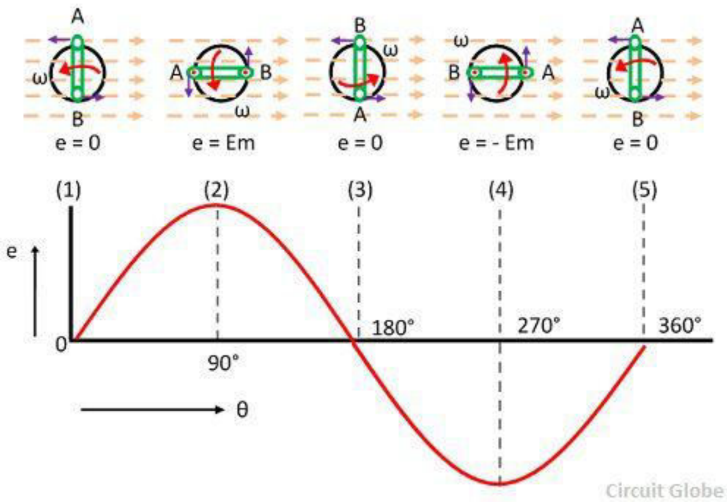
1. At 270 degrees the flux linkage through the loop is once again zero,
2. but the rate of change of flux is maximum.
3. In this position, the EMF induced goes up to its peak value, but this time it's in the reverse direction.

<u>At 360 degrees Position(5):</u>



Position **5** : $(\theta = 0^{o})$minimum $\frac{d\emptyset}{dt}$

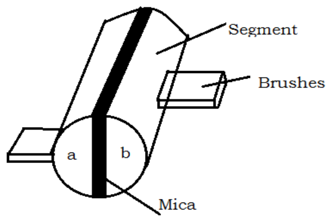
1. The loop is rotated through another 90 degrees such that it has completed a rotation of 360 degrees.
2. The flux linkage through it is maximum and the voltage decreases back to zero.



- Hence, it is observed that the nature of the emf induced in the armature coil is alternating quantity (i.e, positive voltage during first half cycle and negative voltage during second half cycle)
- Thus, to convert the induced alternating ac to dc nature the Commutator (or) split rings are used in the place of the slip rings of a simple loop generator.

ACTION OF COMMUTATOR:

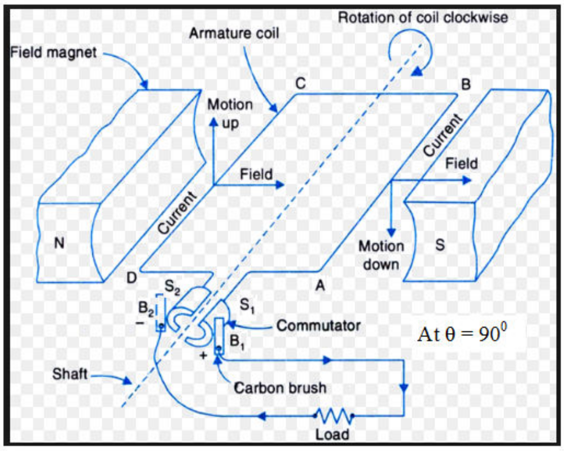
- The Commutator is a mechanical rectifier used to convert AC to DC

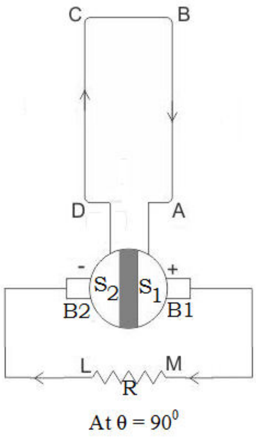


- Here, the split rings or Commutator segments (s_1 and s_2) are placed instead of slip rings
- The split rings or commutator are made out of conducting cylinder, which is cut into two halves or segments insulated from each other by a thin sheet of mica.
- Brushes B_1 and B_2 are mounted on two Commutator segments having + and - polarities

At $\theta = 90^0$position :

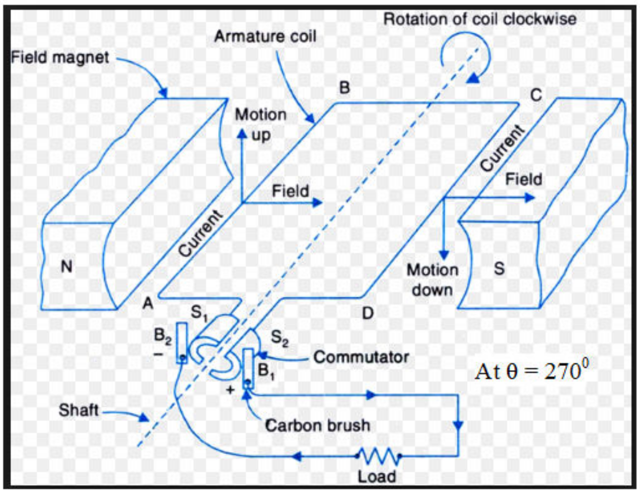
- Conductor AB is under South Pole and Conductor CD are under North Pole, with coil rotating in clock wise direction.
- Using Flemings right hand rule, the current in the conductor AB is from B-A and in conductor CD is from D-C
- Therefore the current flow is in the path of A – S_1 - B_1 – **M – L** - B_2 - S_2 – D – C – B - A

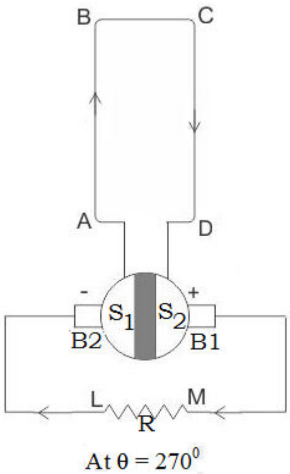


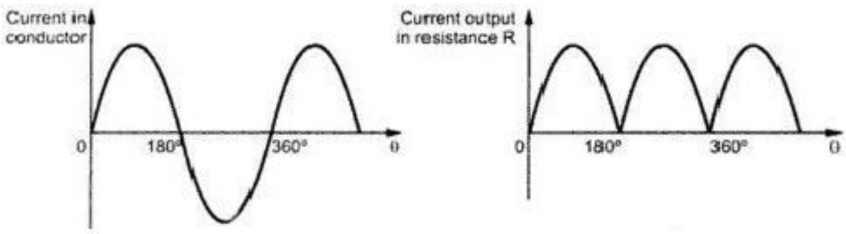


At θ = 270^0position :

- Conductor AB is under North Pole and Conductor CD are under South Pole, with coil rotating in clock wise direction.
- Using Flemings right hand rule, the current in the conductor AB is from A-B and in conductor CD is from C-D
- Therefore the current flow is in the path of A – B – C - D- S_2- B_1 – **M – L** - B_2 – S_1- A





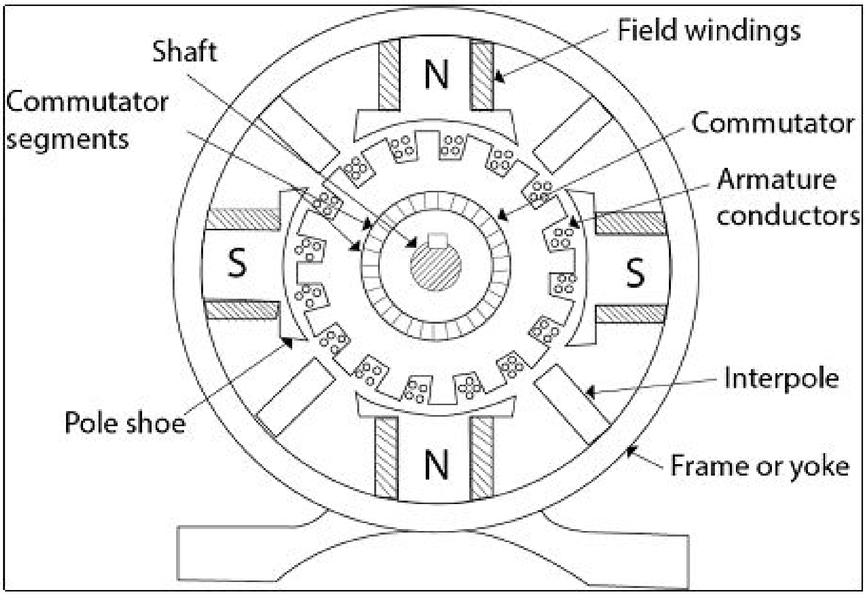


- Thus using the Commutator, the current in the load is unidirectional from M to L at all positions i.e current in coil is alternating and current in Resistance R is unidirectional (pulsating DC)

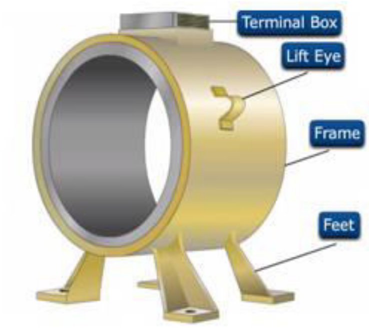
<u>CONSTRUCTION OF DC GENERATOR</u>

A DC generator has the following parts

1. Yoke (or) Magnetic frame
2. Pole core and pole shoe
3. Field winding (or) Pole coils
4. Armature Core
5. Armature winding
6. Commutator
7. Brushes
8. Bearing

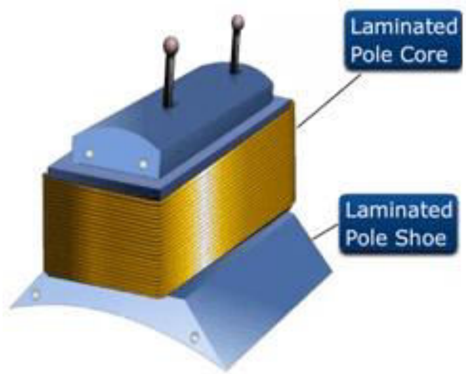


<u>Yoke:</u>



- Yoke or the outer frame of DC generator serves two purposes,
  1. It holds the magnetic pole cores of the generator and acts as cover of the generator.
  2. It carries the magnetic field flux.
- Yoke is made of cast iron for small rating generators, due to the cheaper in cost but heavier than steel.
- Yoke is made of lighter cast steel or rolled steel for larger rating generators , where weight of the machine is concerned.

<u>Pole core and pole shoe</u>



- The field magnets consist of pole cores and pole shoes.
- The pole core is fixed to the inner periphery of the yoke by means of bolts through the yoke and into the pole body.
- The pole core carries the field winding and there are two types of construction

  One: Solid pole core, where it is made of a single piece of cast iron or cast steel.

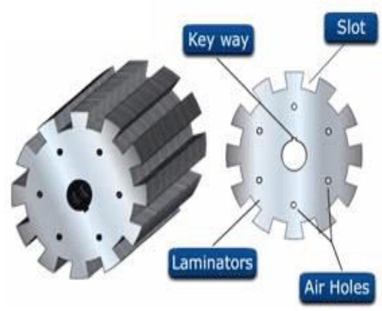
  Two: Laminated pole core, where it made of numbers of thin, limitations of annealed steel which are riveted together.
- The thickness of the lamination is in the range of 0.04" to 0.01".
- The ***pole shoes*** serve two purposes:

1. They spread out the flux in the air gap and also, being of larger cross-section, reduce the reluctance of the magnetic path
2. They support the exciting coils (or field coils)

Field winding (or) Pole coils

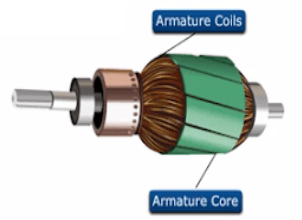
- The function of the field system is to produce uniform magnetic field within which the armature rotates.
- Field coils are mounted on the poles and carry the dc exciting current.
- The field coils are connected in such a way that adjacent poles have opposite polarity.
- The m.m.f. developed by the field coils produces a magnetic flux that passes through the pole pieces, the air gap, the armature and the frame.
- Practical d.c. machines have air gaps ranging from 0.5 mm to 1.5 mm.
- By reducing the length of air gap, we can reduce the size of field coils

Armature Core



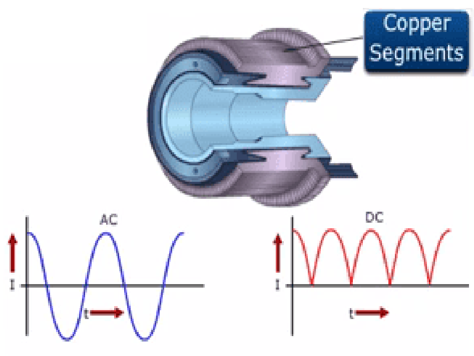
- The armature core consists of slotted soft-iron laminations (about 0.4 to 0.6 mm thick) that are stacked to form a cylindrical core as shown in adjacent figure.
- The purpose of laminating the core is to reduce the eddy current loss.
- Thinner the lamination, greater is the resistance offered to the induced e.m.f., smaller the current and hence lesser the I^2R loss in the core.
- The laminations are slotted to accommodate and provide mechanical security to the armature winding and to give shorter air gap for the flux to cross between the pole face and the armature "teeth".

Armature winding



- The slots of the armature core hold insulated conductors that are connected in a suitable manner. This is known as armature winding.
- This is the winding in which "working" emf is induced. The armature conductors are connected in series-parallel; the conductors being connected in series so as to increase the voltage and in parallel paths so as to increase the current.
- The armature winding of a D.C. machine is a closed-circuit winding; the conductors being connected in a symmetrical manner forming a closed loop or series of closed loops.
- There are two types of armature winding based on the connection to the Commutator they are (a) Lap winding and (b) Wave winding

Commutator

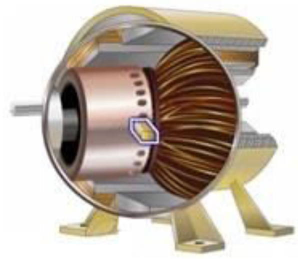


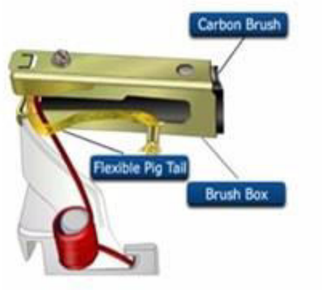
- A Commutator is a mechanical rectifier which converts the alternating voltage generated in the armature winding into direct voltage across the brushes
- The Commutator is made of copper segments insulated from each other by mica sheets and mounted on the shaft of the machine
- The armature conductors are soldered to the

Commutator segments in a suitable manner to give rise to the armature winding

Brushes

- The function of the brushes in DC generator is to collect current from Commutator segments.
- The brushes are made of carbon and rest on the Commutator.
- The brush pressure is adjusted by means of adjustable springs.





Bearing of DC Generator

- For small machine, ball bearing is used and for heavy duty DC generator, roller bearing is used.

The bearing must always be lubricated properly for smooth operation and long life of generator.

EMF EQUATION

Let,

E = Average emf induced in volts
Z = No. of armature conductors
N = Speed of the rotor in RPM
P = No. of the poles
A = No. of parallel paths
Φ = Flux per pole in Weber's

As per Faradays second Law,

- The magnitude of the induced emf (e) is directly proportional to the rate of change of flux linkages (ψ)

$$e\alpha \frac{d\Psi}{dt} = e\alpha\, N\frac{d\Phi}{dt} = e = k\, N\frac{d\Phi}{dt}, \text{ In SI unit system } k=1, \qquad \therefore e = N\frac{d\Phi}{dt}$$

- Emf per conductor is $e = \frac{d\Phi}{dt}$

Where,

- $d\Phi$ = total flux in the airgap that cuts the conductor for one revolution.

  As (P) No. of poles and each pole produces the Φ flux, then $d\Phi = P\Phi$
- dt = time taken by the conductor to cut the flux of $d\Phi$

  i.e The time taken for the armature coil to complete one rotation $dt = \frac{60}{N}\text{sec}$

Thus,

$$e = \frac{P\phi}{\left(\frac{60}{N}\right)} = \frac{P\phi N}{60}$$

As there are (A) No. of parallel paths with 'Z' No. of conductors, then the emf per parallel path is given by

$$e = \frac{P\phi N}{60} * \left(\frac{Z}{A}\right) = \frac{\phi ZN}{60} * \frac{P}{A}$$

Therefore, average value of the emf induced is $E = \frac{\phi ZN}{60} * \frac{P}{A}$

The No. of parallel paths in the armature winding depends on the type of the armature windings

For Wave connected Armature (A=2)

$$E = \frac{\phi ZN}{60} * \frac{P}{2}$$

For Lap connected Armature (A=P)

$$E = \frac{\phi ZN}{60} * \frac{P}{P}$$

Differences between LAP and WAVE windings

Lap Winding	Wave Winding
The lap winding can be defined as a coil which can be lap back toward the succeeding coil.	The wave winding can be defined as the loop of the winding can form the signal shape.
The connection of the lap winding is, the armature coil end is connected to the nearby section on the commutators.	The connection of the wave winding is, the armature coil end is connected to commutator sections at some distance apart.
The numbers of the parallel paths are equal to the total of number poles.	The number of parallel paths is equal to two.
Another name of lap winding is **multiple winding** otherwise **Parallel Winding**	Another name of wave winding is **Series Winding** otherwise Two-circuit
The e.m.f of lap winding is Less	The e.m.f of wave winding is More
The no. of brushes in lap winding is Equivalent to the no. of parallel paths.	The no. of brushes in wave winding is Equivalent toTwo
The types of lap winding are **Simplex lap winding** & Duplex lap winding.	The types of wave winding are **Progressive & Retrogressive**
The efficiency of the lap winding is Less	The efficiency of the wave winding is High
The additional coil used in the lap winding is Equalizer Ring	The additional coil used in the wave winding is Dummy coil
The winding cost of the lap winding is High	The winding cost of the wave winding is Low
The **lap winding used for** high current, low voltage machines.	The **applications of wave winding** include low current and high voltage machines.

TYPES OF DC GENERATORS

Based on the excitation given to the field winding, the dc generators are classified in to two types

a. Separately excited dc generator
b. Self excited dc generator

SEPARATELY EXCITED DC GENERATOR:

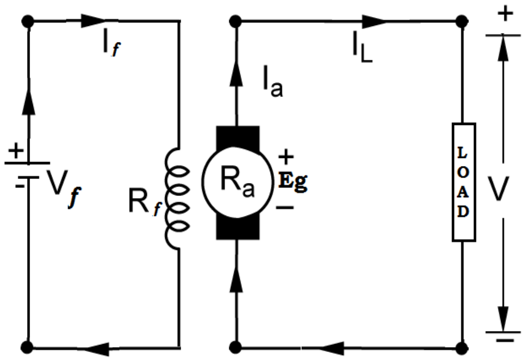
1. In a separately excited generator field winding is energized from a separate voltage source in order to produce flux in the machine and is shown in the below figure.

2. The flux produced will be proportional to the field current in unsaturated condition of the poles.
3. The armature conductors when rotated in this field will cuts the magnetic flux and generates the emf (Eg).
4. The emf will circulate the current against the armature resistance (Ra), brushes and to the load.
5. Applying KVL to the armature loop the Eg is

$$E_g = V + I_a R_a + V_{brush}$$

$I_a = I_L$ and $I_L = \frac{P_L}{V}$ and

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



SELF EXCITED DC GENERATOR:

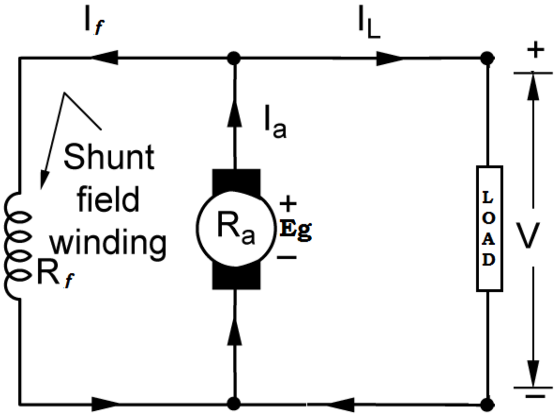
1. In self excited generator field winding is energized from the armature induced emf and there is an electrical connection in between this armature and field winding.
2. There are three possibilities of connecting the field winding to the armature they are
   a. Shunt generator
   b. Series generator
   c. Compound generator
      i. Long shunt compound generator
      ii. Short shunt compound generator

DC SHUNT GENERATOR

1. In the dc shunt generator the field winding circuit is connected in parallel to the armature circuit and as well as to the load.
2. The armature current is divided in to the field and the load as I_f and I_L.
3. The shunt field winding has ***more number of turns with thin wire***, so that resistance of the field will be in the range of hundreds and was designed to withstand for the rated voltage.
4. Applying KVL to the armature loop the E_g is

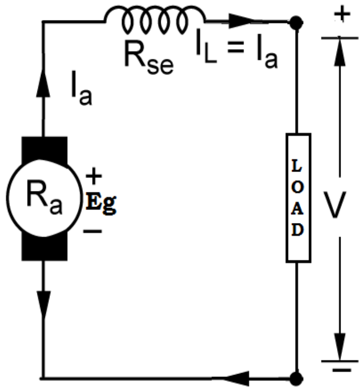
$$E_g = V + I_a R_a + V_{brush}$$

$I_a = I_L + I_f$ and $I_L = \frac{P_L}{V}$ and $I_f = \frac{V}{R_f}$



DC SERIES GENERATOR

1. In the dc series generator the field winding circuit is connected in series to the armature circuit and as well as to the load.
2. Here the armature current is equal to the series field current and also equal to the load.

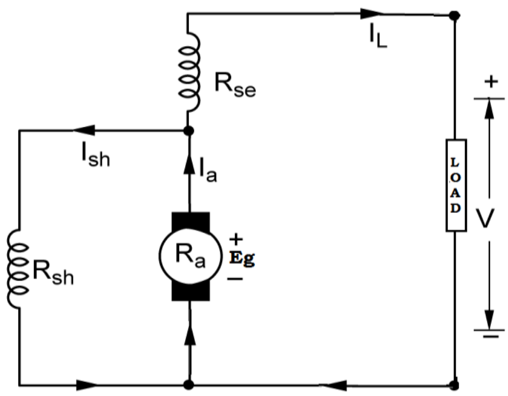


5. The series field winding has ***less number of turns with thick wire***, so that resistance of the field will be in the smaller values and was designed to carry the rated current.
6. Applying KVL to the armature loop the E_g is
$$E_g = V + I_a(R_a + R_{se}) + V_{brush}$$
$$I_a = I_L = I_{se} \quad \text{and} \quad I_L = \frac{P_L}{V}$$

<u>DC COMPOUND GENERATORS</u>

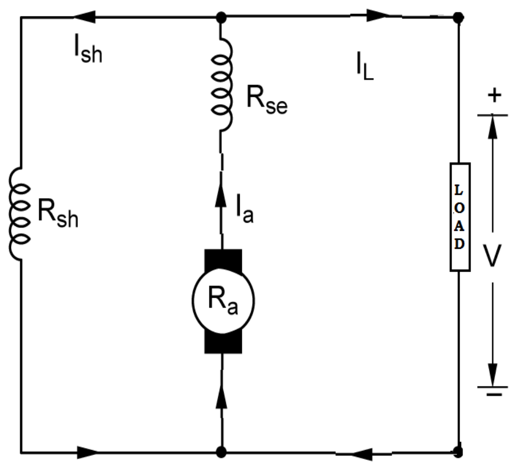
1. A compound generator has two field coils wound over the field poles.
2. The coil having large number of turns and thinner cross sectional area is called the shunt field coil and the other coil having few numbers of turns and large cross sectional area is called the series field coil.
3. Based on the series field winding connected to the armature the compound generators are classified as long shunt generator and short shunt generator

<u>Short Shunt DC Compound Generator</u>



1. In a short shunt dc compound generator, the series field is connected in series to the load and shunt field winding is connected in parallel to the armature and the series combination of the load and series winding.
2. Thus, the series field current will depend on the load variations which will effect in further the shunt field current.
3. Applying KVL to the armature loop the E_g is
$$E_g = V + I_aR_a + I_LR_{se} + V_{brush}$$
$$I_a = I_L + I_{se} \quad \text{and} \quad I_L = \frac{P_L}{V} \quad \text{and} \quad I_f = \frac{V + I_LR_{se}}{R_f}$$

<u>Long Shunt DC Compound Generator</u>

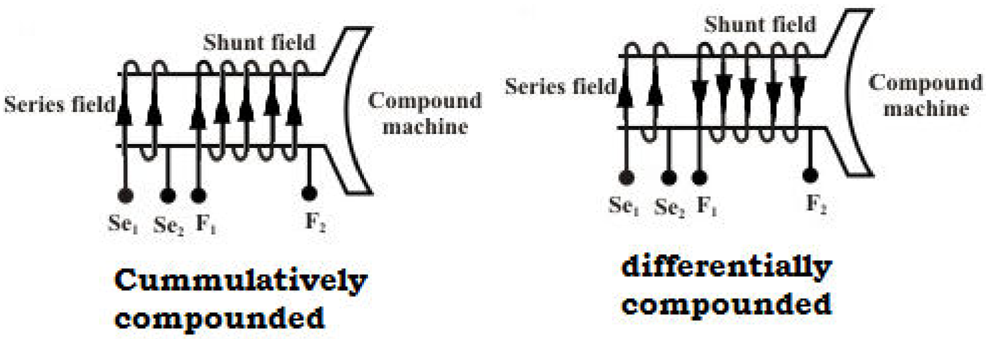


1. In a long shunt dc compound generator, the series field is connected in series to the armature and shunt field winding is connected in parallel to the armature and to the load.
2. Applying KVL to the armature loop the E_g is
$$E_g = V + I_a(R_a + R_{se}) + V_{brush}$$
$$I_a = I_L + I_{se} \quad \text{and} \quad I_L = \frac{P_L}{V} \quad \text{and}$$
$$I_f = \frac{V}{R_f}$$

- Also, the dc compound generators are further classified into two types based on the compounding of the series flux to the shunt flux. They are cumulatively compounded and differentially compounded generators
- In the cumulatively compound generator, the series flux aids to the shunt field flux and the

net flux increases, whereas in the differentially compounded generators the series flux opposes the shunt field flux and the net resultant flux decreases.

- The below figure shows the arrangement of the series and shunt field coils iin the pole core in both cumulative and differentially compounded generators.

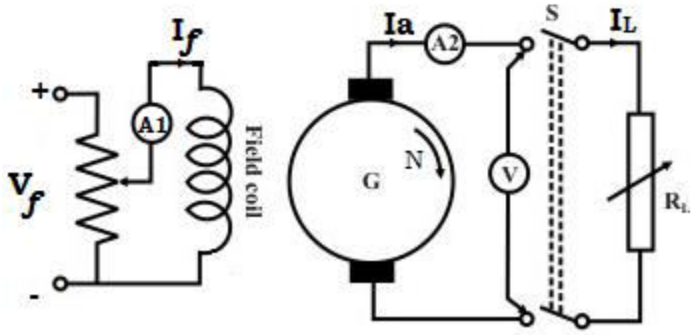


CHARACTERISTICS OF DC GENERATOR

There are three characteristics to be analyzed for any type of the dc generator, they are

1. Open circuit characteristics (or) No-Load characteristics (or) Magnetization characteristics (E_0 *Vs* I_f)
2. Internal characteristics (E_g *Vs* I_a)
3. External or Load characteristics (V *Vs* I_L)

OCC or No-Load Characteristics of Separately excited DC Generator :



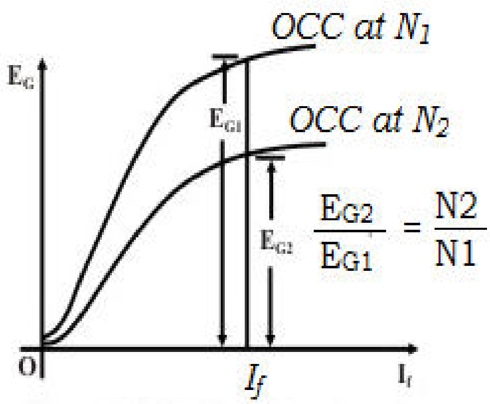
1. OCC is the characteristics drawn between open circuit voltage (E_0) for various field currents (I_f) at constant speed.
2. In this generator field winding is excited from a separate source V_f as shown in above circuit, hence field current is independent of armature terminal voltage
3. The generator is driven by a prime mover at rated speed, say constant speed *N* rpm.
4. With switch *S* in opened condition, field coil is excited via a *potential divider* connection from a separate d.c source and field current is gradually increased by moving the wiper from minimum position gradually.
5. The field current will establish the flux per pole Φ.
6. The voltmeter V connected across the armature terminals of the machine will record the generated emf $\left(E = \frac{PZ}{60A} * \phi N = k * \phi N\right)$. Where *k* is a constant of the machine.

7. As field current is increased, E_0 will increase.
8. E_0 versus I_f plot at constant speed N *rpm* is shown in below figure.
9. It may be noted that even when there is no field current, a small voltage (OD) is generated due to *residual flux* and the small voltage is called *residual voltage.*
10. If field current is increased, φ increases linearly initially and O.C.C follows a straight line.
11. However, when saturation sets in, φ practically becomes constant and hence E*g* too becomes constant.
12. In other words, O.C.C follows the B-H characteristic, hence this characteristic is sometimes also called the magnetization characteristic of the machine.

<u>Procedure to draw OCC at different speeds</u>

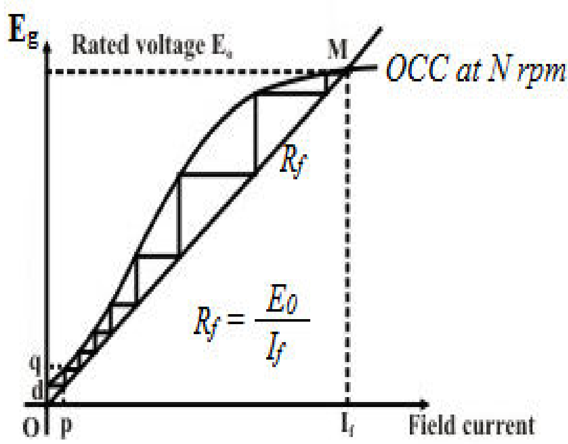
1. It is important to note that if O.C.C is known at a certain speed N_1, O.C.C at another speed N_2 can easily be predicted from the emf equation $E = k*\phi N$
2. Emf at speed N_1 rpm for a field current of I_f, producing the flux Φ is E_1 and is given by $E_1 = k*\phi N_1$
3. Emf at speed N_2 rpm for the same field current of I_f, producing the flux Φ is E_2 and is given by $E_2 = k*\phi N_2$
4. Therefore, the emf E_2 at speed N_2 is

$$\frac{E_2}{E_1} = \frac{k*\phi N_2}{k*\phi N_1} \Rightarrow \frac{E_2}{E_1} = \frac{N_2}{N_1} \Rightarrow E_2 = E_1 \times \frac{N_2}{N_1}$$



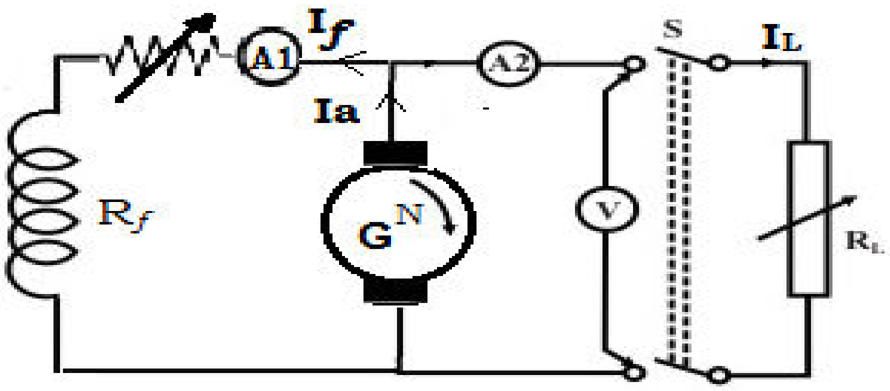
<u>EMF BULID P PROCESS IN A SELF EXCITED DC GENERATOR</u>

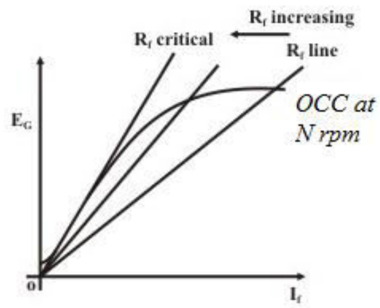
1. For the buildup of emf in the self excited dc generator, the poles or magnets ***must have residual flux*** in them.
2. Therefore, if the generator is driven at rated speed of N rpm, then a small voltage ($k\varphi_{res}N$) will be induced across the armature.
3. This small voltage will be directly applied across the field circuit since it is connected in parallel with the armature.
4. Hence a small field current flows producing additional flux.



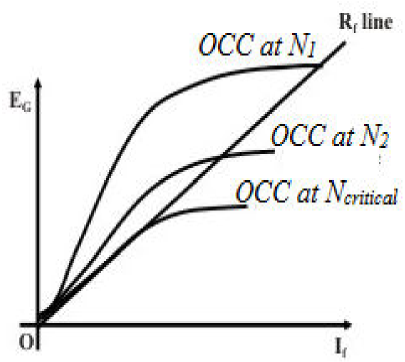
5. If it so happens that this additional flux aids the already existing residual flux, total flux now becomes more and generating more voltage.
6. This more voltage will drive more field current generating more voltage.
7. Both field current and armature generated voltage grow *cumulatively*.
8. This process will be explained clearly from the plot shown above
9. Initially voltage induced due to residual flux is observed from O.C.C as Od.
10. The field current thus produced can be obtained from field circuit resistance line and given by Op. With this Op filed current the flux is increased and correspondingly the induced voltage also increases from Od to Oq and so on. In this way voltage build up process continues along the stair case.

<u>OCC or No-Load Characteristics of self excited DC shunt Generator</u>





1. The OCC of the shunt generator is obtained in a similar way to the dc separately excited generator by disconnecting its field winding from the armature and connecting it to a separate dc source
2. Therefore, the OCC curve at rated speed N rpm is shown in the above figure, with Od as residual voltage and increases gradually.
3. Later, the R_f line is drawn which is a straight line passing through the origin having a slope of its value R_f
4. This R_f line intersects the OCC at point M and gives the rated voltage of the generator.
5. If the R_f value is increased then its slope increases and the voltage generated by the generator reduces and if the value of the R_f is such that it becomes the tangential to the given OCC, then the field resistance is called critical field resistance($R_{f\,critical}$).



6. At this critical field resistance, the emf or voltage of the generator will be very small and it doesn't generates any voltage if the R_f selected is greater than the R_{fc}
7. Thus, ***R_f must be always less than the R_{fc}***
8. Similarly, for the $R_f < R_{fc}$, if the speed decreases then also the voltage generated by the generator reduces.
9. Thus the generator doesn't generates any voltage at a speed called critical speed for which the given R_f line will become the tangent for the OCC drawn at N_c and is shown in the fig.
10. If the speed of the generator is made to run less than its critical speed then no emf will be induced, so the ***speed must be always greater than the critical speed.***

Conditions to build up the emf in the generator:

1. The magnets in the machine must have the ***residual flux.***
2. Field winding connection should be such that the residual flux is strengthened by the field current in the coil. If due to this, no voltage is being built up, reverse the field terminal connection.
3. Total field circuit resistance ***must be less than the critical field resistance.***
4. Speed of the generator ***must be greater than the critical speed.***

APPLICATIONS OF D.C.GENERATORS

Separately Excited DC Generators

1. Because of their ability of giving wide range of voltage output, they are generally used for testing purpose in the laboratories.
2. Separately excited generators operate in a stable condition with any variation in field excitation. Because of this property they are used as supply source of DC motors, whose speeds are to be controlled for various applications. Example- Ward Leonard Systems of speed control.

Applications of Shunt Wound DC Generators

- The application of shunt generators is very much restricted for its dropping voltage characteristic.
- They are used to supply power to the apparatus situated very close to its position.
- These types of DC generators generally give constant terminal voltage for small distance operation with the help of field regulators from no load to full load.

1. They are used for general lighting.
2. They are used to charge battery because they can be made to give constant output voltage.

3. They are used for giving the excitation to the alternators.
4. They are also used for small power supply (such as a portable generator).

Applications of Series Wound DC Generators

- These types of generators are restricted for the use of power supply because of their increasing terminal voltage characteristic with the increase in load current from no load to full load.
- They give constant current in the dropping portion of the characteristic curve. Because of this property they can be used as constant current source and employed for various applications.

1. They are used for supplying field excitation current in DC locomotives for regenerative breaking.
2. These are used as boosters to compensate the voltage drop in the feeder in various types of distribution systems such as railway service.
3. In series arc lightening this type of generators are mainly used.

Applications of Compound Wound DC Generators

- Among various types of DC generators, the compound wound DC generators are most widely used because of its compensating property.
- Depending upon number of series field turns, the cumulatively compounded generators may be over compounded, flat compounded and under compounded.
- Thus the desired terminal voltage can be obtained by compensating the voltage drop due to armature reaction and ohmic drop in the in the line.

  Such generators have various applications.

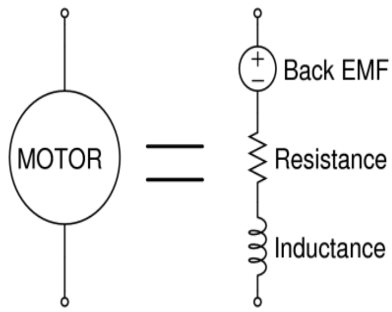
  1. Cumulative compound wound generators are generally used for lighting, power supply purpose and for heavy power services because of their constant voltage property. They are mainly made over compounded.
  2. Cumulative compound wound generators are also used for driving a motor.
  3. For small distance operation, such as power supply for hotels, offices, homes and lodges, the flat compounded generators are generally used.
  4. The differential compound wound generators, because of their large demagnetization armature reaction, are used for arc welding where huge voltage drop and constant current is required.

WORKING PRINCIPLE OF DC MOTOR

- A dc motor is a electro mechanical energy conversion device that converts *electrical energy into mechanical energy.*
- Its operation 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 the force is given by Fleming's left hand rule which states that " Stretch the first three fingers of left hand mutually perpendicular to each other in such a way that central finger indicates the direction of the current in the conductor, fore finger in the direction of the magnetic field, then the thumb indicates the direction of the force developed on the conductor The magnitude of the force developed on the conductor is F = BIL Sinθ

BACK EMF

When the armature of a d.c. motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence an e.m.f. is induced in them as per Faradays laws of electromagnetic induction.



This induced e.m.f. acts in opposite direction to the applied voltage V (Lenz's law) and is known as back or counter e.m.f. E_b .

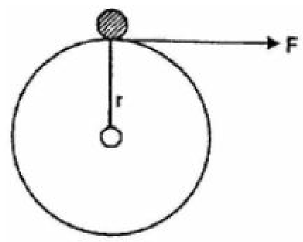
Significance of Back E.M.F

The presence of back e.m.f. makes the d.c. motor a self-regulating machine i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load. Back e.m.f. in a d.c. motor regulates the flow of armature current i.e., it automatically changes the armature current to meet the load requirement.

ARMATURE TORQUE OF A DC MOTOR

Torque is the turning and twisting moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts i.e T = F*r

Let



T = Torque developed on the rotor of the motor in Nm

Φ = Flux per pole in weber

Z = No. of the armature conductors

I_a= Armature current in A

P = No. of poles

A = No. of Parallel paths

r = radius of the pulley in mts

Work done by the pulley, W= Force * distance = F * 2πr

Power = $\frac{\text{work done}}{\text{time}}$ P = $\frac{F\times 2\pi r}{60/N} = \frac{F\times 2\pi r\times N}{60} = \frac{2\pi N}{60}\times(F*r) = \frac{2\pi NT}{60} = \omega T \Rightarrow P = \omega T$

As, power developed in the armature is the gross mechanical power and is given by

P = $E_g I_a$, therefore $E_g I_a = \omega T$

$$\frac{\phi ZN}{60}\left(\frac{P}{A}\right)I_a = \frac{2\pi NT}{60} \quad \because \mathrm{E_g} = \frac{\phi ZN}{60}\left(\frac{P}{A}\right)$$

$$\frac{\phi Z}{2\pi}\left(\frac{P}{A}\right)I_a = T$$

$$\therefore T = \frac{\phi Z}{2\pi}\left(\frac{P}{A}\right)I_a$$

$$T = \frac{1}{2\pi}\phi Z I_a \frac{P}{A}$$

Also, from the fundamentals, the gross torque or armature torque is

$$P = \omega T \Rightarrow E_b I_a = \omega T$$

$$T = \frac{E_b I_a}{\omega} = \frac{E_b I_a * 60}{2\pi N} = \left(\frac{60}{2\pi}\right)*\frac{E_b I_a}{N} = 9.55\frac{E_b I_a}{N} = 9.55\frac{P_m}{N}$$

Also, the shaft torque or useful torque is

$$P_{sh} = \omega T_{sh}$$

$$T_{sh} = \frac{P_{sh}}{\omega} = \frac{P_m - Mechloss}{\omega} = \left(\frac{60}{2\pi}\right)*\frac{P_{sh}}{N} = 9.55\frac{P_{sh}}{N}$$

Therefore,

$$T \,\alpha\, \phi I_a$$

Torque relations in a dc motor

$$\frac{T_2}{T_2} = \frac{\phi_2 I_{a2}}{\phi_1 I_{a1}}$$

<u>Speed of a DC Motor</u>

$$\mathrm{E_b = V - I_a R_a}$$

But $$\mathrm{E_b = \frac{P\phi ZN}{60\ A}}$$

$$\therefore \quad \mathrm{\frac{P\phi ZN}{60\ A} = V - I_a R_a}$$

or $$\mathrm{N = \frac{(V - I_a R_a)}{\phi}\frac{60\ A}{PZ}}$$

or $$\mathrm{N = K\frac{(V - I_a R_a)}{\phi}} \quad \text{where} \quad \mathrm{K = \frac{60\,A}{PZ}}$$

But $V - I_a R_a = E_a$

$\therefore \quad N = K\frac{E_b}{\phi}$

or $N \propto \frac{E_b}{\phi}$

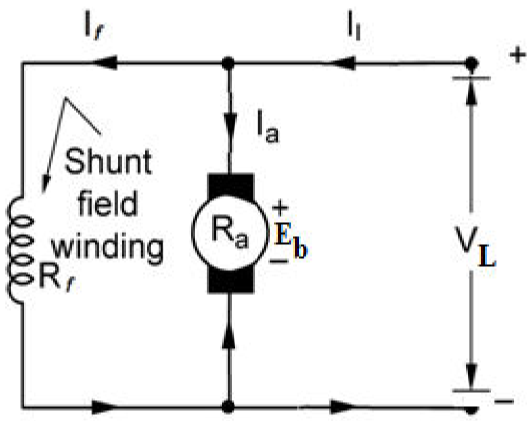
Therefore,
In a dc motor speed is directly proportional to back emf, E_b and inversely proportional to flux, φ.

TYPES OF D.C. MOTORS

Based on the field winding excited from the armature the dc motors are of three types

1. DC Shunt motor
2. DC Series motor
3. DC compound motor
   a. Long Shunt Compound motor
   b. Short Shunt Compound motor

DC SHUNT MOTOR

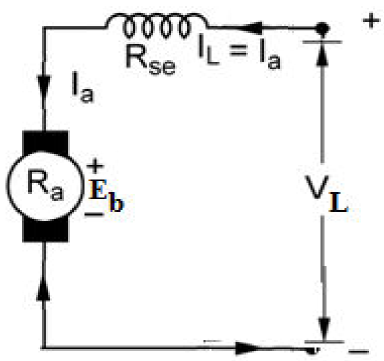


1. In the dc shunt motor the field winding circuit is connected in parallel to the armature circuit and as well as to the line.
2. The line current I_L is divided in to the field and the armature as I_f and I_a.
3. The shunt field winding has ***more number of turns with thin wire***, so that resistance of the field will be in the range of hundreds and was designed to withstand for the rated voltage.
4. Applying KVL to the armature loop the E_g is

$$E_b = V_L - I_a R_a - V_{brush}$$

$I_a = I_L - I_f$ and $I_L = \frac{P_L}{V}$ and $I_f = \frac{V}{R_f}$

DC SERIES MOTOR



3. In the dc series motor the field winding circuit is connected in series to the armature circuit and as well as to the line.
4. Here the armature current is equal to the series field current and also equal to the line.
7. The series field winding has ***less number of turns with thick wire***, so that resistance of the field will be in the smaller values and was designed to carry the rated current.
8. Applying KVL to the armature loop the E_g is

$$E_b = V_L - I_a(R_a + R_{se}) - V_{brush}$$

$I_a = I_L = I_{se}$ and $I_L = \frac{P_L}{V}$

DC COMPOUND MOTORS

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5. The coil having large number of turns and thinner cross sectional area is called the shunt field coil and the other coil having few numbers of turns and large cross sectional area is called the series field coil.
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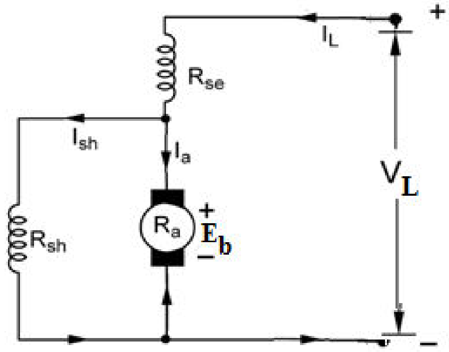
- ***SHORT SHUNT MOTOR***



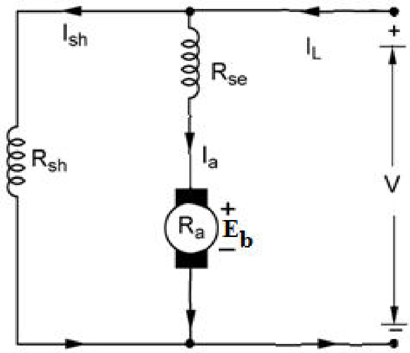
4. In a short shunt dc compound motor, the series field is connected in series to the line and shunt field winding is connected in parallel to the armature and the series combination of the line and series winding.
5. Thus, the series field current will depend on the line variations which will effect in further the shunt field current.
6. Applying KVL to the armature loop the E_g is

$$E_b = V_L - I_a R_a - I_L R_{se} - V_{brush}$$

$$I_a = I_L - I_f \quad \text{and} \quad I_L = \frac{P_L}{V} \quad \text{and}$$

$$I_f = \frac{V_L - I_L R_{se}}{R_f}$$

- ***LONG SHUNT MOTOR***



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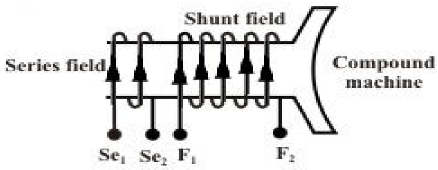
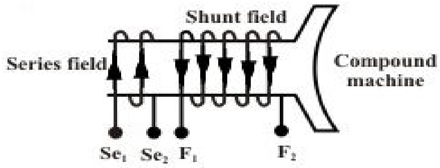
- Also, the dc compound motors are further classified into two types based on the compounding of the series flux to the shunt flux. They are cumulatively compounded and differentially compounded motors
- In the cumulatively compound motor, the series flux aids to the shunt field flux and the net flux increases, whereas in the differentially compounded motors the series flux opposes the shunt field flux and the net resultant flux decreases.
- The below figure shows the arrangement of the series and shunt field coils in the pole core in both cumulative and differentially compounded motors.



Cummulatively compounded



differentially compounded

APPLICATIONS OF D.C. MOTORS

1. Shunt motors

The characteristic of a shunt motor is an approximately constant speed motor. So, it is used where the speed is required to remain almost constant from no-load to full-load

***Industrial applications of shunt motor*:**

1. Lathes
2. Drills
3. Boring mills
4. Shapers
5. Spinning and weaving machines etc.

2. Series motors

It is a variable speed motor i.e., speed is low at high torque and vice-versa. It is used

(i) Where large starting torque is required e.g., in elevators and electric Traction

(ii) Where the load is subjected to heavy fluctuations and the speed is automatically required to reduce at high torques and vice-versa

***Industrial applications of series motor*:**

1. Electric traction
2. Cranes
3. Elevators,
4. Air compressors,
5. Vacuum cleaners
6. Hair drier
7. Sewing machines etc.

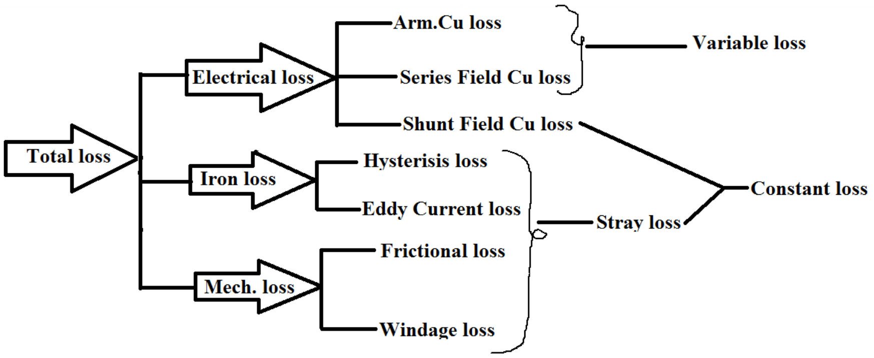
3. Compound motors

Differential-compound motors are rarely used because of their poor torque characteristics. However, cumulative-compound motors are used where a fairly constant speed is required with irregular loads or suddenly applied heavy loads.

***Industrial applications of Compound motor*:**

1. Presses,
2. Shears,
3. Reciprocating machines etc.

LOSSES IN DC MACHINE



Power Stages in DC Generator:

The power stages in a d.c. generator are represented diagrammatically in below Fig.

Mechanical Input - Electrical Power generated = A - B = Iron and friction losses

Electrical Power generated - Electrical Power output = B - C = Copper losses

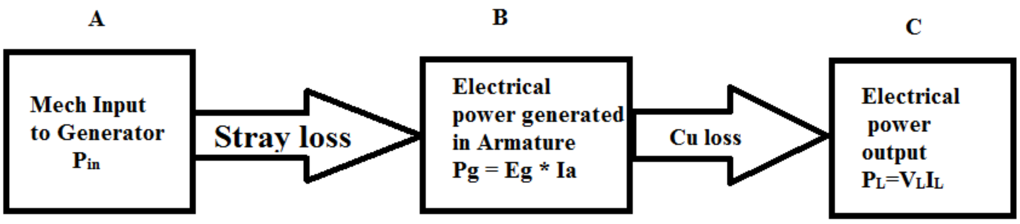
Efficiency is defined as the ratio of output power to the input power

Electrical efficiency, η_e = C/B

Mechanical efficiency, η_m = B/A

Overall efficiency, η_c = C/A

Therefore, Overall efficiency = Electrical efficiency * Mechanical efficiency



Power Stages in DC Motor:

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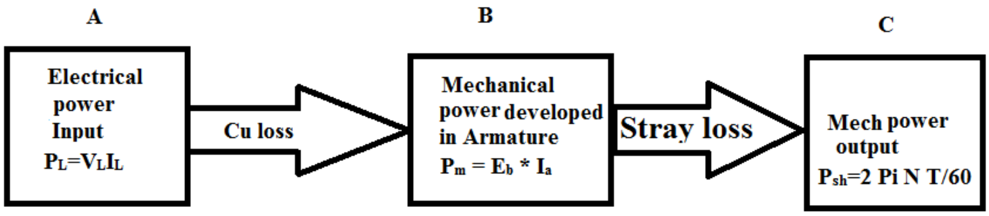
Mechanical power developed - Mechanical power output = B - C = Iron and friction losses



Electrical efficiency η_e = B/A

Mechanical efficiency η_m = C/B

Overall efficiency η_c = C/A

Condition for maximum efficiency for dc motor:

We assume that field current I_f remains constant during change of loading. Let,

$$P_{rot} = \text{constant rotational loss}$$
$$V I_f = \text{constant field copper loss}$$
$$\text{Constant loss } P_{const} = P_{rot} + V I_f$$
$$\text{Now, input power drawn from supply} = V I_L$$
$$\text{Power loss in the armature,} = I_a^2 r_a$$
$$\text{Net mechanical output power} = VI_L - I_a^2 r_a - (VI_f + P_{rot})$$
$$= VI_L - I_a^2 r_a - P_{const}$$
$$\text{so, efficiency at this load current } \eta_m = \frac{VI_L - I_a^2 r_a - P_{const}}{VI_L}$$

Now the armature copper loss $I_a^2 r_a$ can be approximated to $I_L^2 r_a$ as $I_a \approx I_L$. This is because the order of field current may be 3 to 5% of the rated current. Except for very lightly loaded motor, this assumption is reasonably fair. Therefore replacing I_a by I_f in the above expression for efficiency η_m, we get,

$$\eta_m = \frac{VI_L - I_L^2 r_a - P_{const}}{VI_L}$$
$$= 1 - \frac{I_L r_a}{V} - \frac{P_{const}}{VI_L}$$

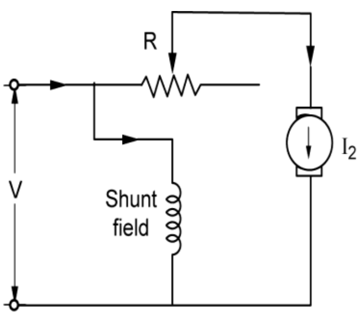
Thus, we get a simplified expression for motor efficiency η_m in terms of the variable current (which depends on degree of loading) I_L, current drawn from the supply. So to find out the condition for maximum efficiency, we have to differentiate η_m with respect to I_L and set it to zero as shown below.

$$\frac{d\eta_m}{dI_L} = 0$$
$$\text{or, } \frac{d}{dI_L}\left(\frac{I_L r_a}{V} - \frac{P_{const}}{VI_L}\right) = 0$$
$$\text{or, } -\frac{r_a}{V} + \frac{P_{const}}{VI_L^2}$$
$$\therefore \text{Condition for maximum efficiency is } I_L^2 r_a \approx I_a^2 r_a = P_{const}$$
$$\text{So, the armature current at which efficiency becomes maximum is } I_a = \sqrt{P_{const}/r_a}$$

Necessity of starter:

- The function of the starter is ***to limit the starting current*** in the motor.

The current drawn by the motor armature is given by $I_a = \frac{V - E_b}{R_a}$



where V is the supply voltage,

E_b is the back emf and

R_a is the armature resistance of the motor.

- At starting, when motor is at rest there is no back emf in the armature (since $E_b \alpha N$)

Now the total supply voltage is applied across the stationary armature and it will draw a very large current because of small armature resistance.

Consider the case of 440 V, 5 HP (3.73 KW) motor having a cold armature resistance of 0.25 Ω and full load current of 50A.

If this motor is started from the line directly, it will draw a starting current of **Fehler!** = 1760 A which is **Fehler!** = 35.2 times its full-load current.

This excessive current will blow out the fuses and damages the commutator and brushes. To avoid this, a resistance is placed in series to the armature for the time duration until the motor pickups the speed.

Once the motor pickups the speed, the back emf is developed and the current was limited by the small voltage (V_L-E_b) applied to the armature against the small resistance.

Thus, the starter is used to limit this starting current by inserting the resistance only at the starting time.

There are three types of starters used namely

3 point starter b) Four point starter c) Two point starter

THREE POINT STARTER

The 3 terminals of the three point starter are marked A, B and C.

First terminal A is connected to the handle arm (L) through the overload release (OLR) from the supply terminals

Second terminal B is connected to the field winding of the motor through the Hold ON coil from the stud 1 of the external resistance placed in series to the armature.

Third terminal C is connected to the armature by inserting the external resistance.

The handle initially is at OFF position and when the supply is given, to start the motor the handle is dragged towards the stud 1.

This position of the handle divides the line current into two paths one path to the armature through the current limiting resistance and second path to the field winding.

Thus the current is limited by this resistance placed in series with the armature. Also as the speed picks up, the handle was dragged over the studs from off position to ON position.

At this ON position all the external resistance is removed from the armature and the spring on the other side of the handle develops the restraining torque with the spring placed.

The soft iron piece (S) on the handle is attracted by the hold on coil in normal running conditions

The resistance that was removed from the armature circuit will be added to the field circuit. Thus the field current is reduced, to overcome the drawback of weakening of the flux the field winding terminal is connected from the brass arc placed below the studs and is shown in the figure

Hold ON coil (or) No Volt Release (NVR)

The Normal function of the HOLD-ON coil is to hold on the arm in then full running position when the motor is in normal operation.

When the supply failure (or) disconnection, it is de-energised, so that handle is released from the hold on coil and pulled back by the spring to the OFF position.

The Hold ON coil protects the motor from dangerous speed when field circuit opens.

Over Load Release (OLR)

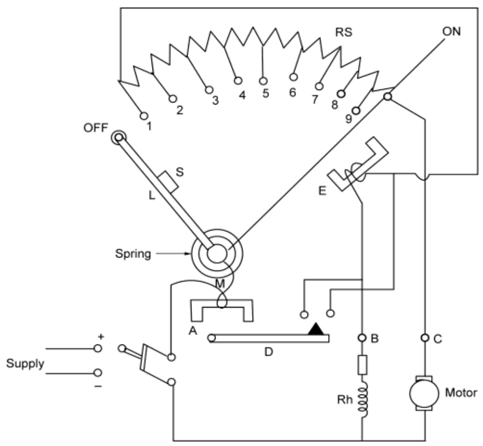
It consists of an electro-magnet connected in the supply line.

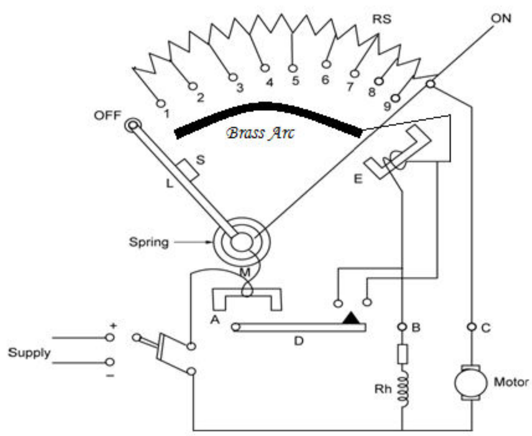
If motor becomes over loaded, then D is lifted and short circuits the electro-magnet. Hence arm is released and returns to OFF position.

Disadvantage of three point starter:

To control the speed of motor, a field rheostat is connected in the field circuit.The motor speed is increased by decreasing the flux ($N \propto I/\phi$). There is a difficulty that if too much resistance is added by the field rheostat, then field current is reduced very much so that the current in the hold on coil is unable to create enough Electromagnetic pull to overcome the spring tension. Hence arm is pulled back to OFF position.

Therefore the shunt motor with this three point starter is not suitable for adjustable speed drive applications.





Speed control of DC motors:

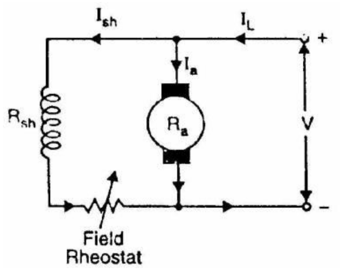
The speed of a d.c. motor is given by:

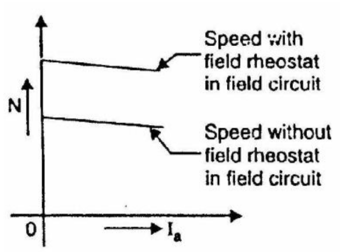
$N\alpha \frac{Eb}{\Phi}$ or $N\alpha \frac{V_L - I_a R}{\Phi}$ where R is Ra for shunt motor and (Ra + Rse). for series motor

From the above expression,
The speed of a d.c. motor is controlled
(i) By varying the flux per pole (f) known as flux control method.
(ii) By varying the R_a and is known as armature control method.
(iii) By varying the applied voltage V and is known as voltage control method.

Speed Control of D.C. Shunt Motor

a) Field control method:





1. In this field control method the variable is flux (f)
2. The rheostat is placed in series to the field winding, as the field resistance increases the field current decreases and this weakens the flux
3. The weakening of the flux increases the speed since speed is inversely proportional to the flux.
4. Thus using the field control, above base speeds can be controlled.
5. This method is also known as constant power method or variable torque method.

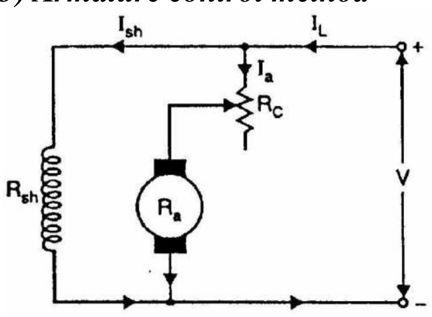
Advantages

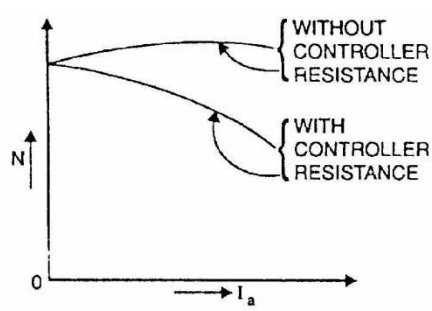
1. This is an easy and convenient method.
2. It is an inexpensive method since very little power is wasted in the shunt field rheostat due to relatively small value of I_f
3. The speed control exercised by this method is independent of load on the machine.

Disadvantages

1. Only speeds higher than the normal speed can be obtained.
2. There is a limit to the maximum speed obtainable by this method. It is because if the flux is too much weakened, commutation becomes poorer.

b) Armature control method





1. In this armature resistance control method the variable is R_a
2. The rheostat is placed in series to the armature winding, as the R_a increases the I_aR_a drop increases and this decreases the speed.
3. The decreasing of the back emf decreases the speed since speed is directly proportional to E_b.

4. Thus using the R_a control method, below base speeds can be controlled.
5. This method is also known as constant torque method or variable power method.

Disadvantages

1. A large amount of power is wasted in the controller resistance since it carries full armature current Ia.
2. The speed varies widely with load since the speed depends upon the voltage drop in the controller resistance and hence on the armature current demanded by the load.
3. The output and efficiency of the motor are reduced.
4. This method results in poor speed regulation.

c) Voltage control method by Ward-Leonard system

1. This method is used to get the wide range of speed control 10:1.
2. As the speed of the motor is directly proportional to the applied voltage to the armature, thus by applying the variable voltage the speed is controlled.
3. The armature of the shunt motor M (whose speed is to be controlled) is connected directly to a d.c. generator G driven by a constant-speed a.c. motor A.
4. The field of the shunt motor is supplied from a constant-voltage exciter E.
5. The field of the generator G is also supplied from the exciter E.
6. The voltage of the generator G can be varied by means of its field regulator.
7. By reversing the field current of generator G by controller FC, the voltage applied to the motor may be reversed.

Advantages

1. The speed of the motor can be adjusted through a wide range without resistance losses which results in high efficiency.
2. The motor can be brought to a standstill quickly, simply by rapidly reducing the voltage of generator G.
3. The disadvantage of the method is that a special motor-generator set is required for each motor and the losses in this set are high if the motor is operating under light loads for long periods.

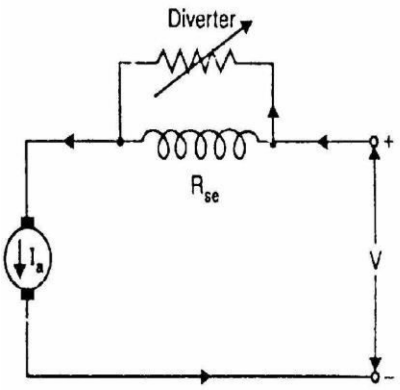
Speed Control of D.C. Series Motor

a) ***Flux control method***

In this method, the flux produced by the series motor is varied and hence the speed.

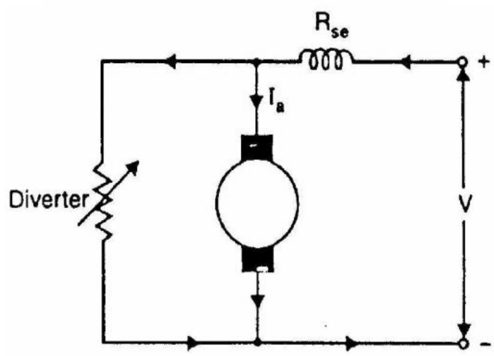
The variation of flux can be achieved in the following ways:

(i) Field diverters.



1. In this method, a variable resistance (called field diverter) is connected in parallel with series field winding as shown in Fig.
2. Its effect is to shunt some portion of the line current from the series field winding, thus weakening the field and increasing the speed ($N \alpha 1/\Phi$).
3. This method can only provide speeds above the normal speed. The series field diverter method is often employed in traction work.

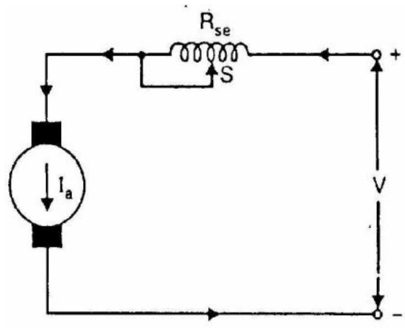
ii) Armature diverter.



1. In order to obtain speeds below the normal speed, a variable resistance (called armature diverter) is connected in parallel with the armature as shown in Fig.
2. The diverter shunts some of the line current, thus reducing the armature current.
3. Now for a given load, if Ia is decreased, the flux Φ must increase ($T \alpha \Phi I_a$).

4. Since (Nα1/Φ). The motor speed is decreased.
5. By adjusting the armature diverter, any speed lower than the normal speed can be obtained.

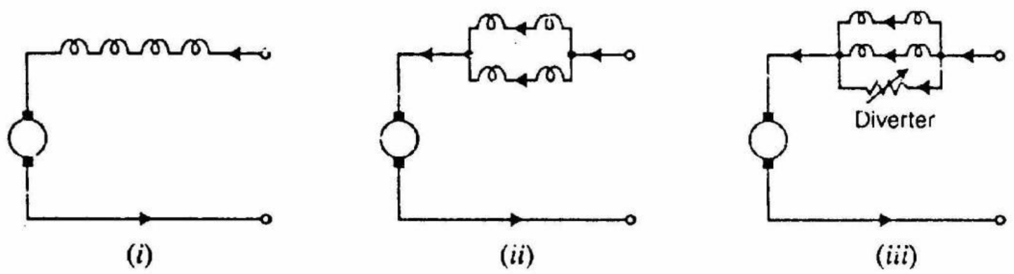
iii) Tapped field control.



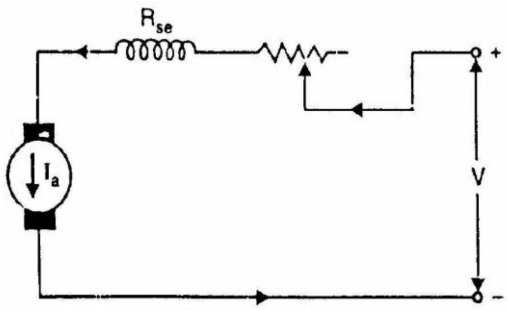
1. In this method, the flux is reduced by decreasing the number of turns of the series field winding as shown in Fig, and hence speed is increased
2. The switch S can short circuit any part of the field winding, thus decreasing the flux and raising the speed.
3. With full turns of the field winding, the motor runs at normal speed and as the field turns are cut out; speeds higher than normal speed are achieved.

iv) Paralleling field coils.

This method is usually employed in the case of fan motors. By regrouping the field coils as shown in Fig below, several fixed speeds can be obtained.



b) Armature-resistance control:



1. In this method, a variable resistance is directly connected in series with the supply to the complete motor as shown in Fig.
2. This reduces the voltage available across the armature and hence the speed falls.
3. By changing the value of variable resistance, any speed below the normal speed can be obtained.
4. This is the most common method employed to control the speed of d.c. series motors.
5. Although this method has poor speed regulation, this has no significance for series motors because they are used in varying speed applications.
6. The loss of power in the series resistance for many applications of series motors is not too serious since in these applications.

TESTING OF DC MACHINES:

Testing of DC machines can be broadly classified as

i) Direct method of Testing

ii) Indirect method of testing

Direct method of testing:

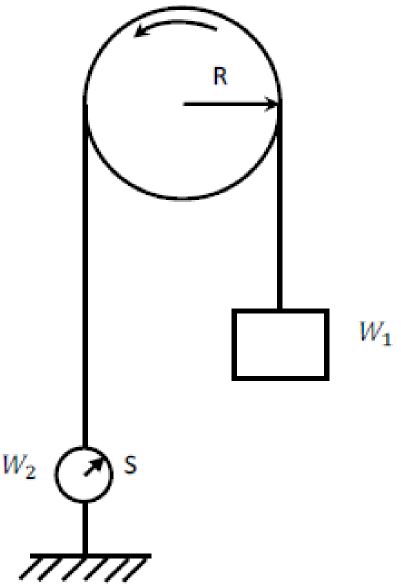
In this method, the DC machine is loaded directly by means of a brake applied to water cooled pulley coupled to the shaft of the machine. The input and output are measured and efficiency is determined by $\eta = \frac{output}{input}$

It is not practically possible to arrange loads for machines of large capacity.

Indirect method of testing:

In this method, the losses are determined without actual loading the machine. If the losses are known, then efficiency can be determined. Swinburne's test, Hopkinson's test and retardation tests are commonly used on shunt motors.

(i) BRAKE TEST: is a direct method of testing.



In this method of testing motor shaft is coupled to a Water cooled pulley which is loaded by means of weight as shown in figure

W_1= suspended weight in kg

W_2 = Reading in spring balance in kg

R = radius of pulley

N = speed in rpm

V = Supply voltage

I = Full Load Current

Net pull due to friction $= (W_1 - W_2)$ kg

$= 9.81\ (W_1 - W_2)$ Newton 1

Shaft torque $T_{sh} = (W_1 - W_2)R\ kg - mt.$

$= 9.81\ (W_1 - W_2)\ R\ N - mt$ 2

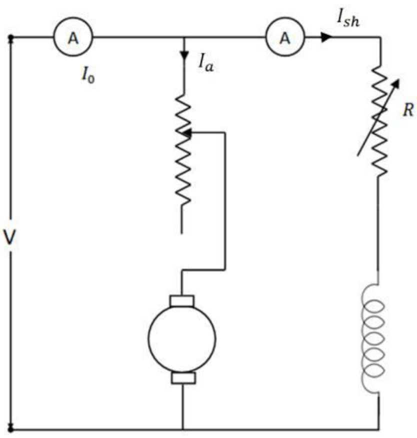
Motor output power $= T_{sh}\ X\ \frac{2\ \pi\ N}{60}$ Watt

Input power = VI watts 3

Therefore efficiency $= \frac{output}{input}$

This method of testing can be used for small motors only because for a large motor it is difficult to arrange for dissipation of heat generated at the brake.

(ii)Swinburne's Test:



This test is a no load test and hence cannot be performed on series motor.
The circuit connection is shown in Figure
The machine is run on no load at rated speed which is adjusted by the shunt field resistance.

Advantages

1. Economical, because no load input power is sufficient to perform the test
2. Efficiency can be pre-determined
3. As it is a no load test, it cannot be done on a dc series motor

Disadvantages

1. Change in iron loss from no load to full load is not taken into account. (Because of armature
reaction, flux is distorted which increases iron losses).
2. Stray load loss cannot be determined by this test and hence efficiency is over estimated.
3. Temperature rise of the machine cannot be determined.
4. The test does not indicate whether commutation would be satisfactory when the machine is loaded.

I_O = No load current; I_{sh} = shunt field current
I_{ao} = No load armature current = $(I_o - I_{sh})$
V= Supply Voltage

No load input $= VI_o$ watts.
No load power input supplies
(i) Iron losses in the core
(ii) Friction and windings loss and
(iii) Armature copper loss.

Let I = load current at which efficiency is required
$I_a = I - I_{sh}$ if machine is motoring; $I + I_{sh}$ if machine is generating
Efficiency as a motor:
Input = VI; $I_a^2 r_a = (I - I_{sh})^2 r_a$
Constant losses $W_c = VI_o - (I_o - I_{sh})^2 r_a$ …………… 7
Total losses $= (I - I_{sh})^2 r_a + W_c$
Therefore efficiency of motor $= \frac{input-losses}{input}; = \frac{VI - ((I-Ish)2ra+Wc)}{VI}$ ……. 8

EFFICIENCY OF A GENERATOR:

Output = VI

$I_a^2 r_a = (I+I_{sh})^2 r_a$

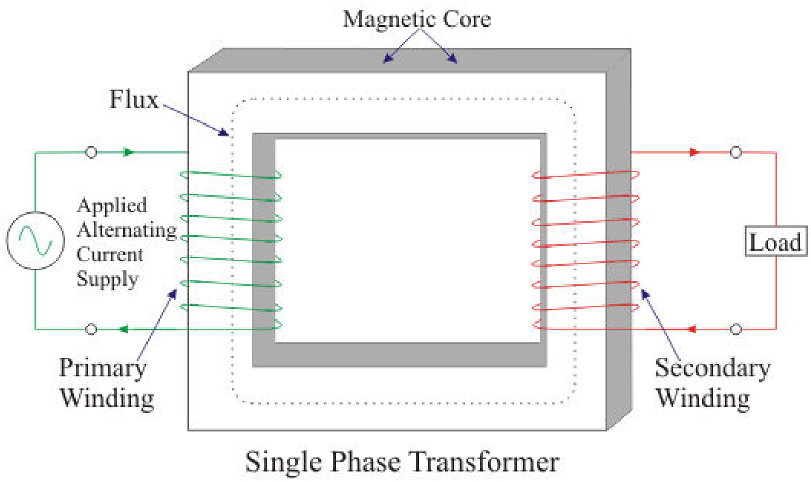
Total losses $= W_c+(I+I_{sh})^2 r_a$ …………………………………….. 9

Efficiency of generator $= \frac{output}{output+losses} = \frac{VI}{VI+(I+I_{sh})^2 r_a + W_c}$ ……… 10

Unit – 2 (BEE) R19&R20 Regulations – I ECE II Semester

Transformers: Principle of operation of single phase transformer constructional features – EMF equation – Losses and efficiency of transformer- regulation of transformer – OC & SC tests predetermination of efficiency and regulations – Sumpner's test-Numerical Problems.

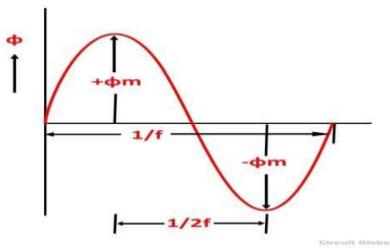
1. Explain the *Working principle* of transformer



Single Phase Transformer

1. The basic working principle of a transformer is mutual induction between two windings linked by common magnetic flux.
2. The primary and secondary coils are electrically separated but magnetically linked to each other.
3. When, primary winding is connected to a source of alternating voltage, alternating magnetic flux is produced around the winding.
4. The core provides magnetic path for the flux, to get linked with the secondary winding. Most of the flux gets linked with the secondary winding which is called as 'useful flux' or main 'flux', and the flux which does not get linked with secondary winding is called as 'leakage flux'.
5. As the flux produced is alternating (the direction of it is continuously changing), EMF gets induced in the secondary winding according to Faraday's law of electromagnetic induction. This induced emf is called 'mutually induced emf', and the frequency of mutually induced emf is same as that of supplied emf. Thus, in a transformer the frequency is same on both sides.
6. If the secondary winding is closed circuit, then mutually induced makes the current flow through it, and hence the electrical energy is transferred from one circuit (primary) to another circuit (secondary).

2. Derive the *EMF Equation* of a Transformer



Let

ϕ_m = Maximum value of flux in Weber

f = Supply frequency in Hz

N_1 = Number of turns in the primary winding

N_2 = Number of turns in the secondary winding

Φ = flux per turn in Weber

As per the faradays laws,

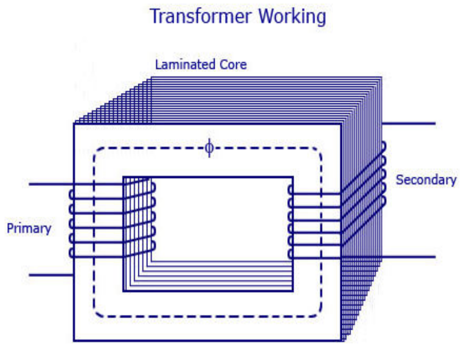
The average value of the emf induced is directly proportional to the rate of change of flux.

- The flux changes from + ϕ_m to – ϕ_m in half a cycle of 1/2f seconds.
- Flux increases from its zero value to maximum value ϕ_m in one quarter of the cycle i.e. in ¼ of the timeperiod.
- Average rate of change of flux is $\frac{d\phi}{dt} = \frac{\phi_m - 0}{\frac{1}{4f}} = 4\phi_m f$ volts

- Therefore the average e.m.f per turn is $4\phi_m f$
- As $\frac{Rmsvalue}{Averagevalue} = Formfactor = 1.11$ for sinusoidal varying quatities
- Hence, RMS value of e.m.f/turn is $1.11 * 4\phi_m f = 4.44\phi_m f$
- RMS value of e.m.f in the primary & secondary winding. =(e.m.f/turn) * No:of turns
- Therefore Emf induced in primary winding having N_1turns is $E_1 = 4.44\phi_m fN_1$
- Emf induced in secondary winding having N_2 turns is $E_2 = 4.44\phi_m fN_2$

3. Explain the *Construction of Transformer*

1. The simple construction of a transformer, need two coils having mutual inductance and a laminated steel core.

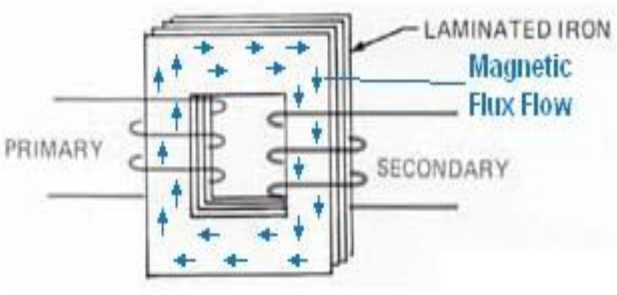


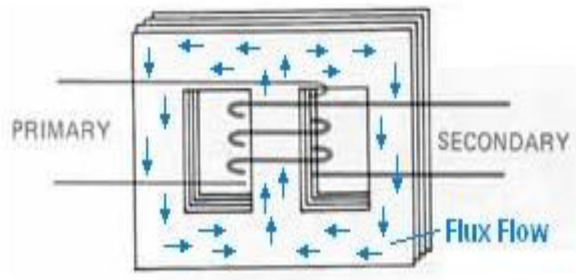
2. The two coils are insulated from each other and from the steel core.
3. The device will also need some suitable container for the assembled core and windings, a medium with which the core and its windings from its container can be insulated.
4. In order to insulate and to bring out the terminals of the winding from the tank, bushings made of porcelain are used.
5. In all transformers, the core is made of transformer sheet steel laminations assembled to provide a continuous magnetic path with minimum of air-gap included.
6. The steel should have high permeability and low hysteresis loss. For this to happen, the steel should be made of high silicon content and must also be heat treated.
7. By effectively laminating the core, the eddy-current losses can be reduced. The lamination can be done with the help of a light coat of core plate varnish or lay an oxide layer on the surface. For a frequency of 50 Hertz, the thickness of the lamination varies from 0.35mm to 0.5mm for a frequency of 25 Hertz.
8. To reduce the leakage fluxes in the transformer the windings of the primary and secondary coils are interleaved in the core type and sandwiched coils in the shell type.
9. To reduce the volume of the cu wire the core used must be the stepped core or cruciform core.

4. Compare and distinguish *the types of transformers*

There are two major types of transformers based on construction. 1. Core type 2. Shell type

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

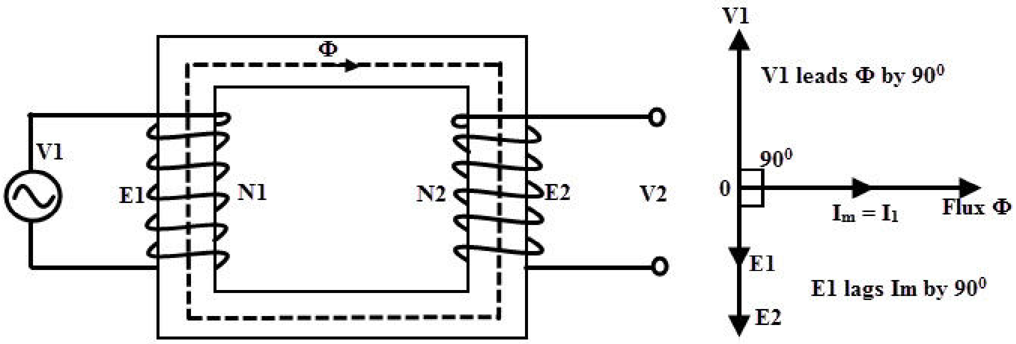




5. Explain the operation of *Transformer on No Load.*

<u>Ideal transformer at No-Load:</u>

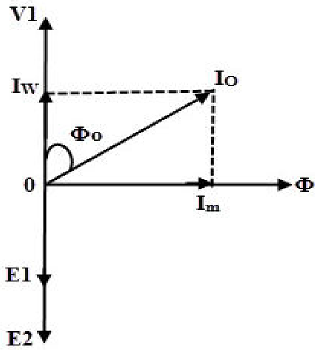
1. The transformer operating at no load, is equivalent to the secondary winding kept open circuited, which means current in the secondary is zero.
2. When primary winding is excited at its rated voltage it draws a current I_m called magnetizing current which is 2 to 10% of the rated current. This generates the magnetic flux in the core by primary mmf N_1I_m
3. As the transformer is ideal, the core loss and cu loss are zero. And the net current taken is to create the mmf or flux of alternating nature.
4. This alternating flux induces the emf's E_1 and E_2 in the coils which lags the flux by 90^0
5. The I_m is inphase to the flux and the applied voltage leads to the I_m by 90^0 being the coil with pure inductive type.
6. Hence, emf's E_1 and E_2 in the coils are inphase to each other and lags the flux by 90^0



Ideal Transformer at No-Load

<u>Transformer at No-Load:</u>

1. The transformer in the practical case draws an additional current I_w to the magnetizing current I_m and total current from the supply mains is I_0 which lags to the applied voltage by an angle Φ_0
2. There are two components of the current in I_0 namely
   i. Active (or) power (or) Watt full component of the current I_w which is in phase to the voltage, and generates the core loss in the transformer
   ii. Reactive (or) Watt less (or) magnetizing component of the current I_m which lags to the voltage by 90^0, and magnetizes the core in the transformer
3. Also, the no-load input power of the transformer is the iron loss (since the cu loss are small at no-load)
4. The no load angle (Φ_0) depends upon the losses in the transformer and is nearly equal to 90^0. So that the power factor is very low and varies from 0.1 to 0.15 lagging.



6.

Working component $I_w = I_0 Cos\varphi_0$

No load current $I_0 = \sqrt{I_w^2 + I_m^2}$

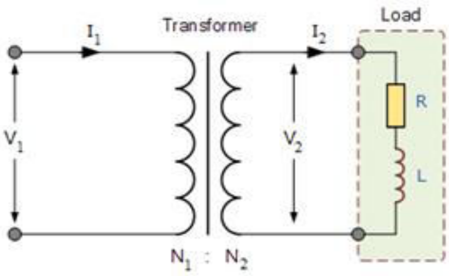
Magnetizing component $I_m = I_0\, Sin\varphi_0$

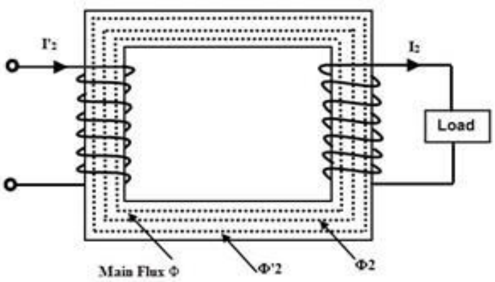
Power factor $Cos\ \varphi_0 = \frac{I_w}{I_0}$

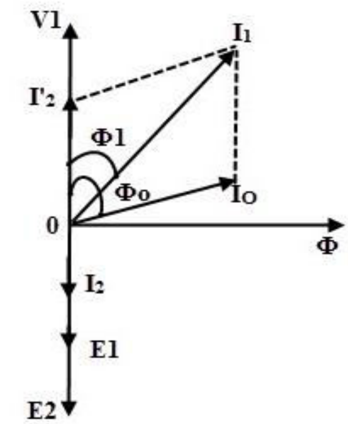
No load power input $P_0 = V_1 I_0 Cos\varphi_0$

6. Explain the operation of Transformer on Load *without leakage impedances* of the coils.

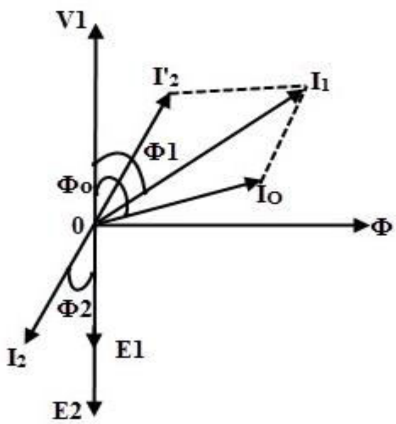
1. When an electrical load is connected to the secondary winding of a transformer a current flows in the secondary winding.
2. This secondary current is due to the induced secondary voltage, set up by the magnetic flux Φ in the core from the primary current(I_0) and the main flux direction is from primary coil to secondary coil (clockwise)



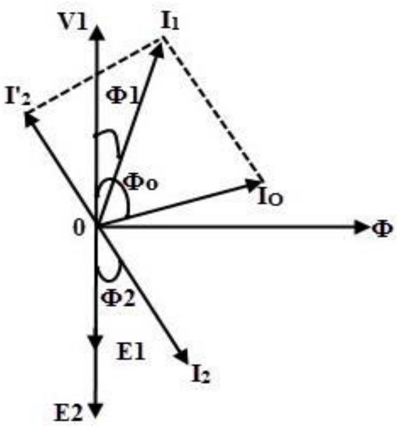




Resistive Load



Inductive Load



Capacitive Load

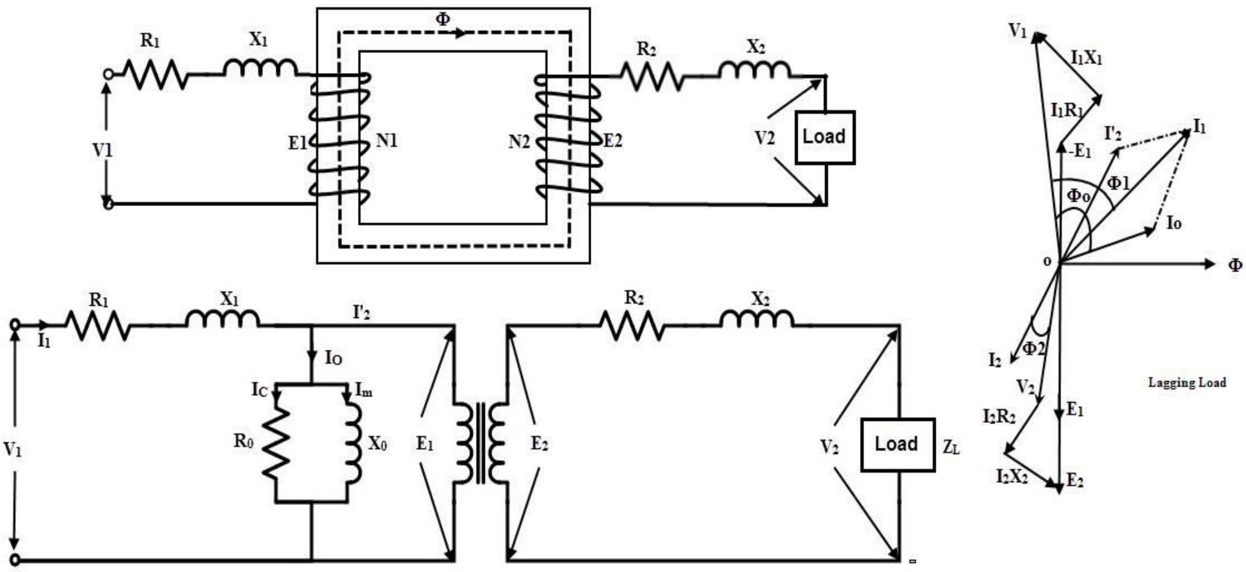
3. The secondary current, I_2 which is determined by the characteristics of the load, creates an secondary or load mmf (N_2I_2) and a secondary magnetic field, Φ_2 is established in the transformer core which flows in the exact opposite direction to the main primary field, Φ_1. i.e Φ_2 is in anti clock wise.
4. These two magnetic fields oppose each other resulting in a combined magnetic field of less magnetic strength than the single field produced by the primary winding alone when the secondary circuit was open circuited.

5. This in turn decreases the primary induced emf and leads to the increase in primary current $I_1=I_0+I_2^1$.
6. This additional I_2^1 current is called load component current in the primary and will be in such a way to balance the load mmf by this mmf on the primary

   i.e $N_2I_2=N_1I_2^1$ therefore $I_2^1= I_2K$ where, $K = N_2/N_1$
7. This $N_1I_2^1$ will produce a flux Φ_2^1 equal and opposite to Φ_2. These fluxes will now be cancelled and the net flux in the core will be Φ_1 even under the loading conditions.
8. For lagging load: $I_1^2 = I_0^2 + (I_2^1)^2 + 2I_0I_2^1\cos(\Phi_0\sim \Phi_2)$
9. As the flux remains constant from no-load to load, the iron loss will be same from no-load to load.

7. Explain the operation of transformer on load with *leakage impedances* of the coils

1. Below figure shows the schematic diagram, equivalent circuit and phasor diagram of the transformer with the leakage impedances of the coils.



Let,

R_1=Resistance of primary coil in Ω *R_2=Resistance of secondary coil in Ω*

X_1=Reactance of primary coil in Ω *X_2=Reactance of secondary coil in Ω*

Z_1=impedance of primary coil in Ω *Z_2=impedance of secondary coil in Ω*

E_1=emf induced in primary coil *E_2=emf induced in secondary coil*

V_1=applied voltage to primary coil *V_2= Load or terminal voltage of transformer*

$I_1Z_1 = I_1(R_1+jX_1)$ = Primary leakage impedance drop

$I_2Z_2 = I_2(R_2+jX_2)$ = Secondary leakage impedance drop

The magnetic core of the transformer is electrically represented with the parallel combination of R_0 and X_0 carrying the currents of I_w and I_m respectively and is placed across the primary coil.

Currents Analysis of the transformer in equivalent circuit

Currents in the transformer at No-load:

$$I_w = \frac{V_1}{R_0} \qquad I_m = \frac{V_1}{X_0} \qquad I_0^2 = I_w^2 + I_m^2 \qquad I_0 = \sqrt{I_w^2 + I_m^2} \qquad \phi_0 = \tan^{-1}\left(\frac{I_m}{I_w}\right)$$

Currents in the transformer with load

$$I_1 = (I_0\angle -\phi_0) + (I_2^1\angle \pm\phi_2) \quad \textit{Where } I_2^1 = I_2 \times K \quad \textit{and} \quad K = \frac{N_2}{N_1}$$

$$I_1 = (I_0\cos\phi_0 + I_2^1\cos\phi_2) + j(I_0\sin(-\phi_0) + I_2^1\sin(\pm\phi_2))$$ - for lag and + for lead

Primary phase angle (Φ_1)

$$\phi_1 = \tan^{-1}\left(\frac{I_0\sin(-\phi_0) + I_2^1\sin(\pm\phi_2)}{I_0\cos\phi_0 + I_2^1\cos\phi_2}\right)$$ *and primary power factor is cosΦ_1*

Voltages Analysis of the transformer in equivalent circuit

Primary induced emf

$$E_1 = (V_1\angle 0) - (I_1\angle\phi_1 * Z_1)$$

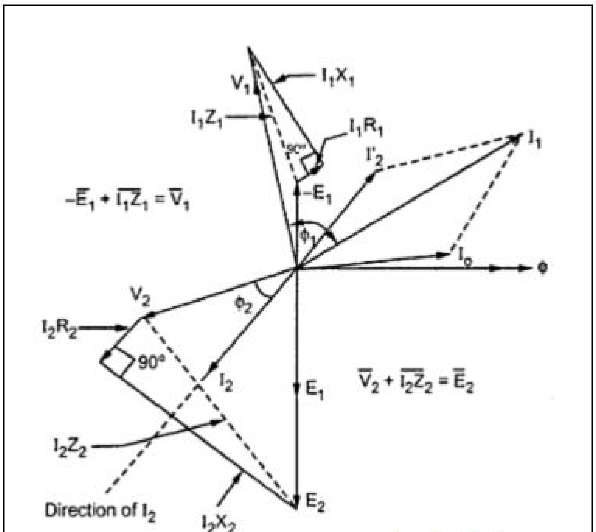
$$E_1 = (V_1 + j0) - \{(I_1\cos\phi_1 + jI_1\sin\phi_1) \times (R_1 + jX_1)\}$$

Using transformation ratio $E_2 = E_1 * K$

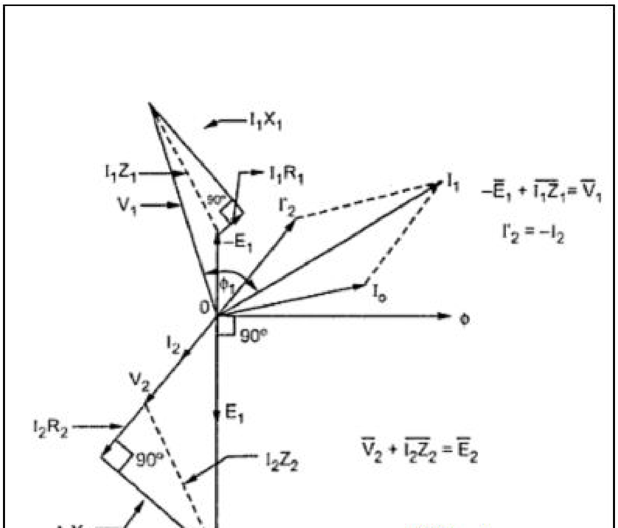
Knowing the E_2 and applying KVL to the secondary loop the load voltage is

$$V_2 = E_2 - I_2 Z_2$$

$$V_2 = E_2\angle\phi' - (I_2\angle\pm\phi_2)Z_2 \qquad V_2 = E_2\angle\phi' - (I_2\angle\pm\phi_2)(R_2 + jX_2)$$



Leading load



UPF load

8. Explain the *equivalent circuits* referred to both primary and secondary of the transformer

The equivalent circuit of the transformer referred to primary is shown in the below figure in which the winding parameters of the secondary are transformed and was referred to primary based on the voltage balancing principle before and after the transformation.

Secondary Resistance referred to primary:

$$R_2^1 = \frac{V_1}{I_1} = \frac{V_1}{I_1} \times \frac{V_2 I_2}{V_2 I_2} = \times \frac{V_1 I_2}{V_2 I_1} \times \frac{V_2}{I_2} = \frac{R_2}{K^2} \qquad \left(\because \frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{1}{K}\right) also \frac{V_2}{I_2} = R_2$$

$\therefore R_2^1 = \frac{R_2}{K^2}$ Thus, it is the secondary resistance referred to primary

Secondary Reactance referred to primary:

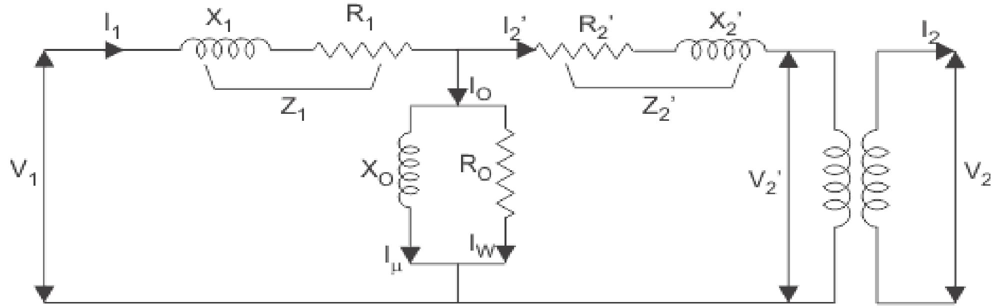
$$X_2^1 = \frac{V_1}{I_1} = \frac{V_1}{I_1} \times \frac{V_2 I_2}{V_2 I_2} = \times \frac{V_1 I_2}{V_2 I_1} \times \frac{V_2}{I_2} = \frac{X_2}{K^2} \qquad \left(\because \frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{1}{K}\right) also \frac{V_2}{I_2} = X_2$$

$\therefore X_2^1 = \frac{X_2}{K^2}$ Thus, it is the secondary reactance referred to primary

Secondary Impedance referred to primary:

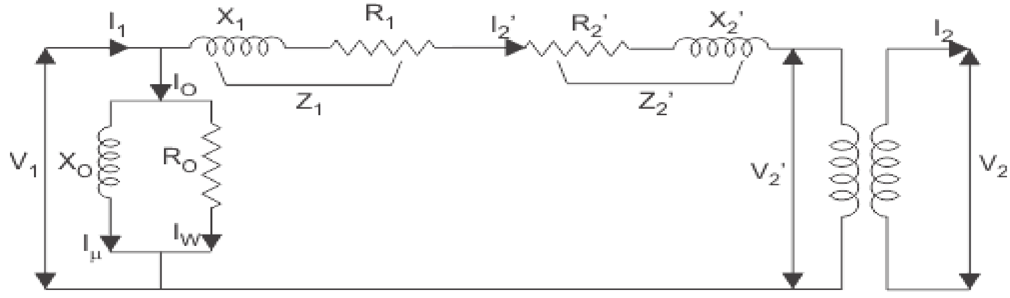
$$Z_2^1 = \frac{V_1}{I_1} = \frac{V_1}{I_1} \times \frac{V_2 I_2}{V_2 I_2} = \times \frac{V_1 I_2}{V_2 I_1} \times \frac{V_2}{I_2} = \frac{Z_2}{K^2} \qquad \left(\because \frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{1}{K}\right) also \frac{V_2}{I_2} = Z_2$$

$\therefore Z_2^1 = \frac{Z_2}{K^2}$ Thus, it is the secondary impedance referred to primary



Equivalent Circuit of Transformer referred to Primary

To have simplified calculations the equivalent circuit is modified as bringing the core branch towards the supply voltage instead of having in between the primary and secondary parameters



simplified equivalent circuit of transformer reffered to primary

In this simplified circuit the total resistance, reactance and impedances referred to primary are

$$\therefore R_{eq1} = R_1 + R_2^1 = R_1 + \frac{R_2}{K^2} \qquad \therefore X_{eq1} = X_1 + X_2^1 = X_1 + \frac{X_2}{K^2}$$

$$\therefore Z_{eq1} = Z_1 + Z_2^1 = Z_1 + \frac{Z_2}{K^2}$$

Similarly, the equivalent circuit referred to secondary of the transformer is shown below with their formulas

Primary Resistance referred to secondary:

$$R_1^1 = \frac{V_2}{I_2} = \frac{V_2}{I_2} \times \frac{V_1 I_1}{V_1 I_1} = \times \frac{V_2 I_1}{V_1 I_2} \times \frac{V_1}{I_1} = K^2 R_1 \qquad \left(\because \frac{V_2}{V_1} = \frac{I_1}{I_2} = K\right) also \frac{V_1}{I_1} = R_1$$

$\therefore R_1^1 = R_1 K^2$ Thus, it is the primary resistance referred to secondary

Primary Reactance referred to secondary:

$$X_1^1 = \frac{V_2}{I_2} = \frac{V_2}{I_2} \times \frac{V_1 I_1}{V_1 I_1} = \times \frac{V_2 I_1}{V_1 I_2} \times \frac{V_1}{I_1} = K^2 X_1 \qquad \left(\because \frac{V_2}{V_1} = \frac{I_1}{I_2} = K\right) also \frac{V_1}{I_1} = X_1$$

$\therefore X_1^1 = X_1 K^2$ Thus, it is the primary reactance referred to secondary

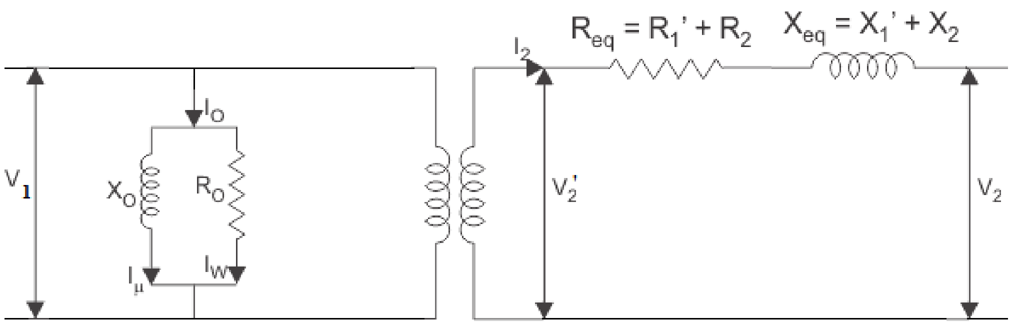
Primary Impedance referred to secondary:

$$Z_1^1 = \frac{V_2}{I_2} = \frac{V_2}{I_2} \times \frac{V_1 I_1}{V_1 I_1} = \times \frac{V_2 I_1}{V_1 I_2} \times \frac{V_1}{I_1} = K^2 Z_1 \qquad \left(\because \frac{V_2}{V_1} = \frac{I_1}{I_2} = K\right) also \frac{V_1}{I_1} = Z_1$$

$\therefore Z_1^1 = Z_1 K^2$ Thus, it is the primary impedance referred to secondary

$$\therefore R_{eq2} = R_2 + R_1^1 = R_2 + R_1 K^2 \qquad \therefore X_{eq2} = X_2 + X_1^1 = X_2 + X_1 K^2$$

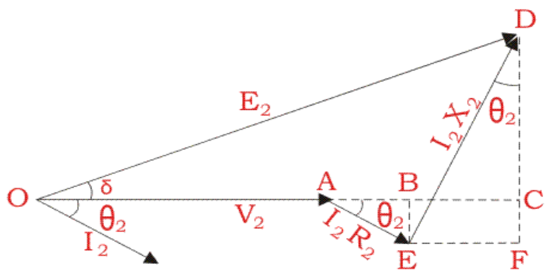
$$\therefore Z_{eq2} = Z_2 + Z_1^1 = Z_2 + Z_1 K^2$$



Approximate Equivalent Circuit of Transformer referred to Secondary

9. Derive the expression for *voltage regulation and efficiency* of the transformer

Definition of voltage regulation : Voltage regulation is defined as the percentage change in the output voltage from no-load to full-load expressed in full load voltage.



$$OC = OA + AB + BC$$

$$Here,\ OA = V_2$$

$$Here,\ AB = AE\cos\theta_2 = I_2 R_2 \cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2 X_2 \sin\theta_2$$

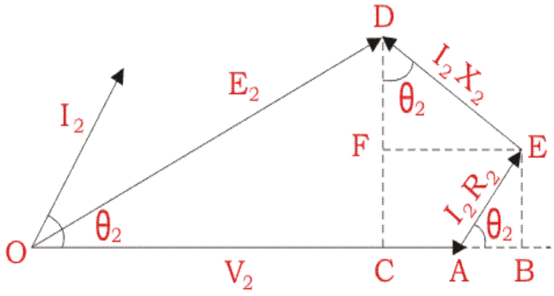
Derivation of voltage regulation for the lagging power factor load,
assuming the angle between OC and OD as very small, and neglected it, OD is nearly equal to OC ($E_2 > V_2$)

$E_2 = OC = OA + AB + BC, \quad E_2 = OC = V_2 + I_2 R_{eq2} \cos\phi + I_2 X_{eq2} \sin\phi$

Thus, the % voltage regulation is

$$\frac{E_2 - V_2}{V_2} * 100 = \frac{V_2 + I_2 R_{eq2} \cos\phi + I_2 X_{eq2} \sin\phi - V_2}{V_2} \times 100 = \frac{I_2 R_{eq2} \cos\phi + I_2 X_{eq2} \sin\phi}{V_2} \times 100$$

Derivation of voltage regulation for the leading power factor load,
Similarly, from the phasor diagram of the leading pf load , ($E_2 < V_2$)



Here

$EF = DE \sin\theta = I_2 X_2 \sin\theta$

$AB = AE \cos\theta = I_2 R_2 \cos\theta$

$OA = V_2$ and $OD = E_2$

assuming the angle between OA and OD as very small, and neglected it, OD is nearly equal to OC ($E_2 < V_2$)

$V_2 - E_2 = OA - OC = CA = CB - AB$, thus $V_2 = E_2 + CB - AB$

Thus, the % voltage regulation is

$$\frac{E_2 - V_2}{V_2} * 100 = \frac{E_2 - E_2 - CB + AB}{V_2} \times 100 = \frac{I_2 R_{eq2} \cos\phi - I_2 X_{eq2} \sin\phi}{V_2} \times 100$$

Therefore,

$$\%regulation = \frac{I_2 R_{eq2} \cos\phi \pm I_2 X_{eq2} \sin\phi}{V_2} \times 100$$ (+) for lagging pf and (-) for leading pf

10. Discuss the losses and efficiency in the transformer

Transformer is a static device, i.e. it doesn't have any parts, so no mechanical losses exist in the transformer and only electrical losses are observed.

So there are two primary types of losses in the transformer:

1. Copper losses
2. Iron losses

Other than these, some small amount of power losses in the form of 'stray losses' are also observed, which are produced due to the leakage of magnetic flux.

Copper losses

1. These losses occur in the windings of the transformer when heat is dissipated due to the current passing through the windings and the internal resistance offered by the windings.
2. So these are also known as ohmic losses or I^2R losses, where 'I' is the current passing through the windings and R is the internal resistance of the windings.
3. These losses are present both in the primary and secondary windings of the transformer and depend upon the load attached across the secondary windings since the current varies with the variation in the load, so these are *variable losses.*

Iron losses or Core Losses

1. These losses occur in the core of the transformer and are generated due to the variations in the flux.
2. These losses depend upon the magnetic properties of the materials which are present in the core, so they are also known as iron losses, as the core of the Transformer is made up of iron. And since they do not change like the load, so these losses are also *constant losses.*

There are two types of Iron losses in the transformer:

1. Eddy Current losses
2. Hysteresis Loss

Eddy Current Losses

1. When an alternating current is supplied to the primary windings of the transformer, it generates an alternating magnetic flux in the winding which is then induced in the secondary winding also through Faraday's law of electromagnetic induction, and is then transferred to the externally connected load.
2. During this process, the other conduction materials of which the core is composed of; also gets linked with this flux and an emf is induced.
3. But this magnetic flux does not contribute anything towards the externally connected load or the output power and is dissipated in the form of heat energy.
4. So such losses are called Eddy Current losses and are mathematically expressed as:

$$P_e = K_e f^2 K_f^2 B_m^2$$

Where;

K_e = Constant of Eddy Current

K_f^2 = Form Constant

B_m = Strength of Magnetic Field

Hysteresis Loss

1. Hysteresis loss is defined as the electrical energy which is required to realign the domains of the ferromagnetic material which is present in the core of the transformer.
2. These domains loose their alignment when an alternating current is supplied to the primary windings of the transformer and the emf is induced in the ferromagnetic material of the core which disturbs the alignment of the domains and afterwards they do not realign properly.
3. For their proper realignment, some external energy supply, usually in the form of current is required. This extra energy is known as Hysteresis loss.

   Mathematically, they can be defined as;

$$P_h = K_h B_m^{1.6} f V$$

- The **Efficiency** of the transformer is defined as the ratio of power output to the input power.

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{output power}}{\text{output power + losses}}$$

$$\eta = \frac{\text{output power}}{\text{output power + iron losses + copper losses}}$$

$$\eta = \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + P_i + P_c}$$

Where,

V_2 = Secondary terminal voltage

I_2 = Full load secondary current in A

$\cos\phi_2$ = power factor of the load

P_i = Iron losses = hysteresis losses + eddy current loss

Pc = Full load copper losses = $I_2^2 R_{eq}$

Also, the efficiency at any amount of load(x) is given by

$$\eta = \frac{outputinwatts}{inputinwatts} = \frac{xVA\cos\phi}{xVA\cos\phi + W_i + x^2 W_{FLCu}} \times 100$$

Condition for maximum efficiency in the transformer:

$$\eta = \frac{outputinwatts}{inputinwatts} = \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + W_i + I_2^2 r_{e2}} = \frac{1}{1 + \frac{W_i}{V_2 I_2 \cos\phi} + \frac{I_2^2 r_{e2}}{V_2 I_2 \cos\phi}} = \frac{1}{1 + \frac{W_i}{V_2 I_2 \cos\phi} + \frac{I_2 r_{e2}}{V_2 \cos\phi}}$$

To get the maximum efficiency the denominator must be small, therefore condition to be the denominator minimum is

$$\frac{d\left(1 + \frac{W_i}{V_2 I_2 \cos\phi} + \frac{I_2 r_{e2}}{V_2 \cos\phi}\right)}{dI_2} = 0$$

$$\frac{d\left(1 + \frac{W_i}{V_2 I_2 \cos\phi} + \frac{I_2 r_{e2}}{V_2 \cos\phi}\right)}{dI_2} = 0 + \left((-)\frac{W_i}{V_2 I_2^2 \cos\phi}\right) + \left(\frac{r_{e2}}{V_2 \cos\phi}\right) = 0$$

$$\frac{r_{e2}}{V_2 \cos\phi} = \frac{W_i}{V_2 I_2^2 \cos\phi} \qquad r_{e2} = \frac{W_i}{I_2^2} \qquad I_2^2 r_{e2} = W_i$$

Therefore the condition for obtaining the maximum efficiency is the variable loss $\left(I_2^2 r_{e2}\right)$ must be equal to the constant loss W_i.

Also, the load current at which the maximum efficiency occurs is $I_{2\max} = \sqrt{\left(\frac{W_i}{r_{e2}}\right)}$

Multiplying both sides with 1000 *V_2

$$1000 * V_2 * I_{2\max} = 1000 * V_2 * \sqrt{\left(\frac{W_i}{r_{e2}}\right)} \qquad \text{Load KVA}_{\max} = 1000 * V_2 * \sqrt{\left(\frac{W_i}{r_{e2}}\right)}$$

$$\text{Load KVA}_{\max} = 1000 * V_2 * \frac{I_{2\text{Fullload}}}{I_{2\text{Fullload}}} \sqrt{\left(\frac{W_i}{r_{e2}}\right)}$$

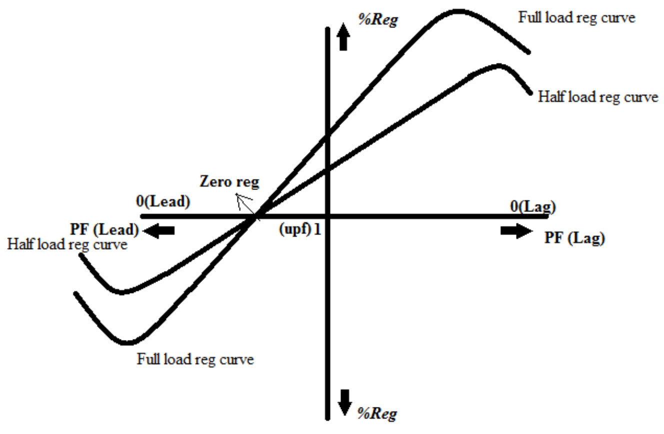
$$\text{Load KVA}_{\max} = 1000 * V_2 * I_{2\text{Fullload}} \sqrt{\left(\frac{W_i}{I_{2\text{Fullload}}^2 r_{e2}}\right)}$$

$$\text{Load KVA}_{\max} = \text{Full load KVA} \sqrt{\left(\frac{W_i}{I_{2\text{Fullload}}^2 r_{e2}}\right)}$$

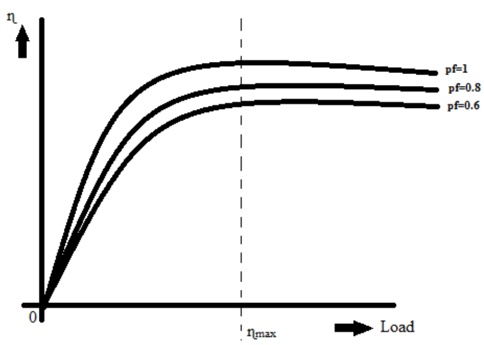
$$\text{The Load KVA at which maximum efficiency} = \text{Full load KVA} \sqrt{\left(\frac{W_i}{W_{\text{cuFullload}}}\right)}$$

$$\text{The Load KVA at which maximum efficiency} = \text{Full load KVA} \sqrt{\frac{W_i}{W_{\text{cuFullload}}}}$$

Variation of voltage regulation and efficiency with respect to load and load powerfactors



Regulation curves w.r.t load pf and amount of loads



Varaiation of efficiency with respect to load and load power factor

11. Explain OC and SC tests on a single phase transformer

Ans: Purpose of conducting OC and SC tests is to find

i) Equivalent circuit parameters ii) Efficiency iii) Regulation

Open Circuit Test:

1. The OC test is performed on LV side at rated voltage and HV side is kept opened.
2. As the test is conducted on LV side the meters selected will be at low range values like smaller voltmeter, smaller ammeter and low pf wattmeter
3. As the no-load current is quite small about 2 to 5% of the rated current, the ammeter required here will be smaller range even after on LV side which are designed for higher current values.
4. The voltmeter, ammeter and the wattmeter readings V_0, I_0 and W_0 respectively are noted by applying rated voltage on LV side.
5. The wattmeter will record the core loss because of noload input power.

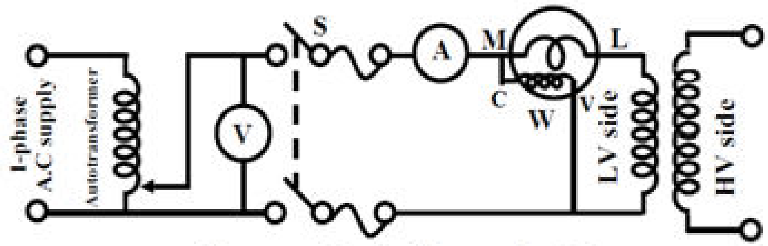


Figure : Circuit diagram for O.C test

Calculations from OC test readings:

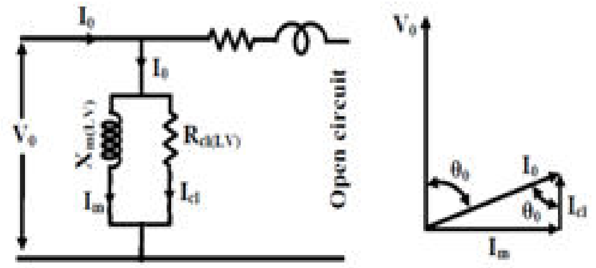
R_0, X_0 and Iron loss are calculated from the OC test results as

Core resistance $R_0 = \frac{V_0}{I_w} = \frac{V_0}{I_0 \cos\phi_0}$

Magnetizing reactance $X_0 = \frac{V_0}{I_m} = \frac{V_0}{I_0 \sin\phi_0}$

Where $\cos\phi_0 = \frac{P_0}{V_0 I_0}$

and iron loss $W_i = P_0$ (No load input power)



(a) Equivalent circuit under O.C test (b) phasor diagram

Figure 2.2: Equivalent circuit & phasor diagram during O.C test

Short Circuit Test:

1. The SC test is performed on HV side at rated current and LV side is kept Shorted.

2. As the test is conducted on HV side the meters selected will be at low range values like smaller voltmeter, smaller ammeter and unity pf wattmeter
3. As the voltage required to circulate the short circuit rated current is very small about 10 to 15% of the rated HV voltage, so the voltmeter required here will be smaller range even the test is conducted on HV side.
4. The voltmeter, ammeter and the wattmeter readings V_{sc}, I_{sc} and W_{sc} respectively are noted by passing rated current on HV side.
5. The wattmeter will record thecopper loss corresponding to the I_{sc}.

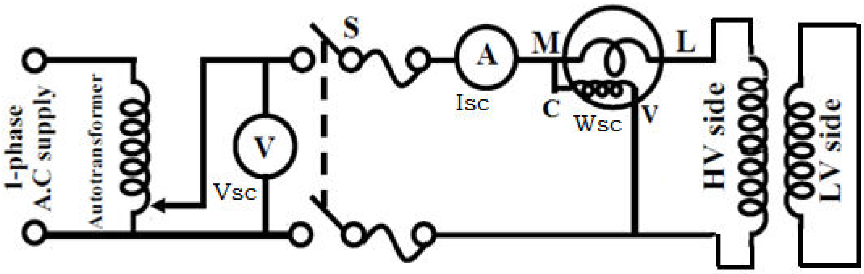
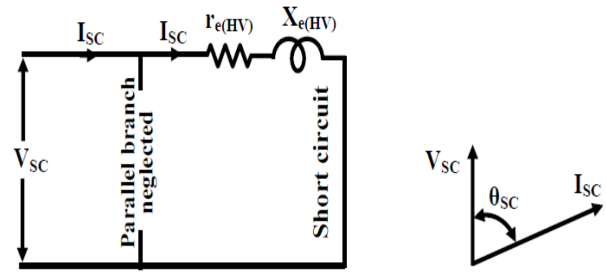


Figure 2.3: Circuit diagram for S.C test



(a) Equivalent circuit under S.C test (b) phasor diagram

Figure 2.4: Equivalent circuit & phasor diagram during S.C test

Calculations from SC test readings:

$r_{e(HV)}$, $x_{e(HV)}$ and cu loss are calculated from the SC test results as

Equivalent resistance referred to HV side is

$$R_{sc} = \frac{P_{sc}}{I_{sc}^{2}} = r_{e(HV)}$$

Equivalent impedance referred to HV side is

$$Z_{sc} = \frac{V_{sc}}{I_{sc}} = z_{e(HV)}$$

Equivalent reactance referred to HV side is $X_{sc} = \sqrt{Z_{sc}^2 - R_{sc}^2} = x_{e(HV)}$

The culoss is equal to the wattmeter reading W_{sc}

- Thus, the approximate equivalent circuit of the transformer can be drawn by the calculated values of R_0 and X_0 on LV side and $r_{e(HV)}$ and $x_{e(HV)}$ *on* HV side.
- The efficiency at any load is calculated from the losses W_i and W_{cufl} as

$$\eta_x = \frac{xVA\cos\phi}{xVA\cos\phi + W_i + x^2 W_{FLCu}} \times 100$$

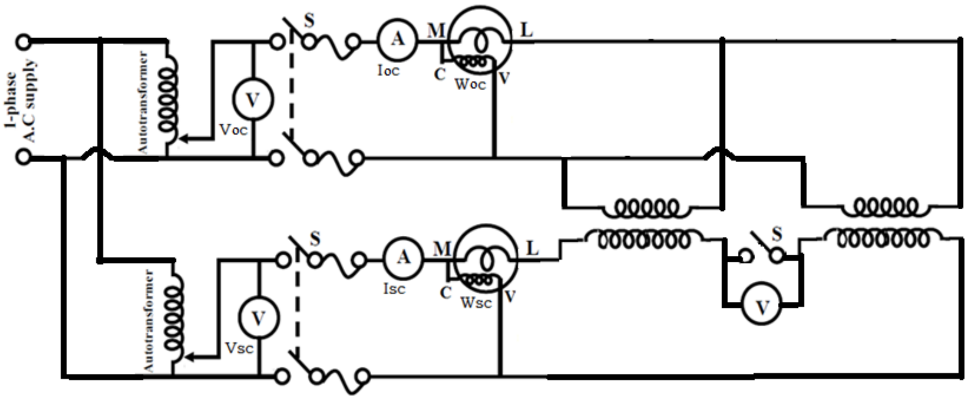
The regulation of the transformer is calculated from the $r_{e(HV)}$ and $x_{e(HV)}$ as

$$\%reg = \frac{I_{HV} r_{eHV} \cos\phi \pm I_{HV} x_{eHV} \sin\phi}{V_{HV}} \times 100 \text{ where } + \text{is for lagging pf and} - \text{is for leading pf}$$

12. Explain Sumpner's test or back to back test

Ans: Purpose of Sumpner's test or back to back test on transformer is to determine efficiency, voltage regulation considering the **heating under loaded** conditions.

1. Two identical transformers are required to conduct the Sumpner's test
2. Both transformers are connected to supply such that one transformer is loaded on another.
3. Both Primaries are connected in parallel and both secondaries are connected in series opposition which is checked by the voltmeter showing zero volts when the switch S is closed.



Procedure for sumpner's test:

1. Both the emf's cancel each other, as transformers are identical. In this case, as per superposition theorem, no current flows through secondary. And thus the no load test is simulated.
2. The current drawn from V_{oc} is $2I_0=I_{oc}$ and the input power measured by wattmeter W_{oc} is equal to iron losses of both transformers. i.e. iron loss per transformer $P_i = W_{oc}/2$.
3. Now, a small voltage V_{sc} is injected into secondary with the help of a low voltage transformer.
4. The voltage V_{sc} is adjusted so that, the rated current I_{sc} flows through the secondary. In this case, both primaries and secondary's carry rated current.
5. Thus short circuit test is simulated and wattmeter W_{sc} shows total full load copper losses of both transformers. i.e. copper loss per transformer $P_{Cu} = W_{sc}/2$.
6. From above test results, the full load efficiency of each transformer is calculated and is given as

$$\%\eta = \frac{xVA\cos\phi}{xVA\cos\phi + \frac{W_{oc}}{2} + x^2\frac{W_{sc}}{2}} \times 100$$

Unit – 3 (BEE) R19&R20 Regulations – I ECE II Semester

Synchronous Generators: Principle of operation and construction of alternators – types of alternators Regulation of alternator by synchronous impedance method-EMF equation of three phase alternator. Synchronous Motors: Construction of three phase synchronous motor - operating principle – equivalent circuit of synchronous motor.

ALTERNATOR - WORKING PRINCIPLE

- Synchronous generator or AC generator is a device which converts mechanical power in the form of A.C.
- It works on the principle of ELECTRO MAGNETIC INDUCTION and it is also called as Alternator.
- An alternator consists of armature winding and field magnet, but the difference between the alternator and DC generator is that in the DC generator armature rotates and the field system is stationary.
- This arrangement in the alternator is just reverse of it, the armature is stationary called as stator and field system is rotating called as Rotor.

For generating EMF, three things are essential:

1) Magnetic field
2) System of conductors
3) Relative motion between those two.

- The conductors are mounted on the stator and the field poles are mounted on the Rotor core
- Relative motion between the stator conductors and the field is brought about rotating the field system.
- The rotor is coupled mechanically to a suitable prime mover. When the prime mover runs, the rotor core also rotates and the field flux is cut by the stationary stator conductors and emf's are induced in them.
- If a load is connected across the stator terminals electric power would be delivered to it.

Advantages of Stationary Armature

1. The generated power can be easily taken out from the stator.
2. There is no possibility of the armature conductors flying of, when the machine runs at high speed since they are housed in the stator slots.
3. There is no difficulty in insulating the armature (stationary) winding for very high voltages, i.e, as high as 30000v or more.
4. Two slip rings are required for the supply of DC energy required for rotor field excitation. Since exciting current is to be supplied at low voltage, there is no difficulty in insulating them.

5. Rotating field is competitively light and can run with high speeds.

Differences between stationary and rotating field systems:

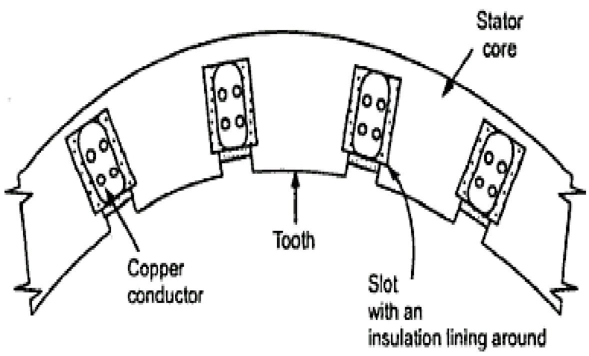
S.No.	STATIONARY FIELD SYSTEM	ROTATING FIELD SYSTEM
1	4 slip rings are required.	100 slip rings are required.
2	Heavy armature current passes through slip rings.	Very low field current passes through slip rings.
3	More sparking at slip rings.	No sparking at slip rings.
4	Armature supply is taken through slip rings.	Armature supply is taken through fixed connections.
5	Capacity is limited to 30KVA.	It can be designed to any capacity.
6	Voltage is limited to 440v.	Voltage is up to 33KV is generated.
7	Low efficiency.	High efficiency.
8	More maintenance.	Less maintenance.

CONSTRUCTION OF ALTERNATOR

An alternator consists of mainly two parts

1. Stator
2. Rotor

Stator:



1. The armature core is supported by the stator frame and is built up of laminations of special magnetic iron or steel iron alloy, the core is laminated to minimize the loss due to Eddy currents.
2. The laminations are stamped out in complete rings or segments. The laminations are insulated from each other and have space between them for allowing the cooling air to pass through.
3. The inner periphery of the stator is slotted and copper conductors which are joined to one another constituting armature winding housed in these slots.
4. The other ends of the winding are brought out are connected to fixed terminal from which the generator power can be taken out.
5. Different shapes of the armature slots are available
   a. The wide open type slot also used in DC machines has the advantage of permitting easy installation of form-wound colis and there easy removal in case of repair but it has the

disadvantage of distributing the air gaps flux into bunches that produce ripples in the wave of generated EMF.

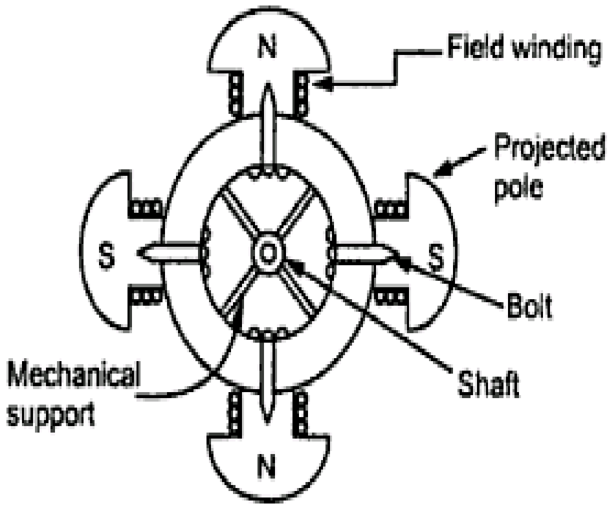
b. The semi closed type slots are better in this respect but do not allow the use of form wound coils.
c. The fully closed slots do not disturb the air gap flux but they try to increase the inductance of the windings. The armature conductors have to be threaded through, thereby increasing the initial labour and cost of the winding. Hence, these are rarely used.

Rotor

Depending upon the type of application, these are classified into two types

1) Salient-pole or projecting pole type
2) Non silent-pole or round rotor or cylindrical rotor

Salient-pole or projecting pole type



1. It is used for low and medium speed alternators used in hydro and diesel power generating station.
2. The poles are made of laminated sheets and fixed to the rotor by dove tail joint.
3. Short circuited damper bars are placed in the slots provided on the pole surfaces.
4. These are used to prevent hunting and to provide starting torque in synchronous motors.
5. The field coils are placed on the poles as shown in the figure

Key features:-

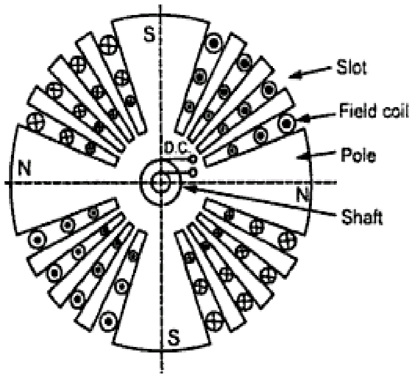
1. It has non-uniform air gap.
2. The diameter of the rotor is more than of the cylindrical rotor.
3. The no. of poles is higher than that of the non salient-pole rotor
4. Axial length is less.
5. The prime mover speed is less and is driven in hydal turbines
6. These generators are used in hydro electric stations so these are called as hydro generators.

Non-Salient pole type (or) Cylindrical type (or) Round rotor:

- Slots are provided in between the poles and these slots are placed with field winding Conductors.

Key Features:

1. No. of poles are less when compared to salient pole type.
2. Diameter is less
3. Axial length is more
4. Air gap is uniform
5. Prime mover speed is more and is driven in thermal turbines.
6. These are used in thermal stations so, these are called as turbo Generators.



FREQUENCY OF THE INDUCED EMF

Consider an alternate whose rotor is driver at a constant speed N rpm.

Let

P = No. of poles in the alternator

f = Frequency of the generated voltage in Hertz (or) Cycles per sec

- $$\text{No. of cycles of the induced EMF per sec} = \frac{\text{No. of Cycles}}{\text{Revolution}} \times \frac{\text{No. of Revolutions}}{\textit{Seconds}}$$

No. of cycles per revolution = No. of pairs of poles = P/2

No. of revolutions per second = N/60

Therefore,

$$\text{Frequency of the induced EMF} = \frac{P/2}{1} \times \frac{N}{60} = \frac{PN}{120}$$

For a given alternator, the no. of poles is fixed. Hence in order to generate power at a specified frequency, the machine is to be run at a definite speed which is termed as synchronous speed.

EMF EQUATION OF ALTERNATOR:

Consider a 3 - Phase alternator with

P = No. of poles

N = Driven speed in rpm.

E = RMS value of the induced emf per pole in Volts.

Ø = Average flux per pole in Webbers

Z_{ph} = No. of stator conductors per phase

T_{ph} = No. of stator turns per phase, also

$T_{ph}=Z_{ph}/2$

"f " is the frequency of induced emf in Hz

- Therefore total flux cut per revolution by any one stator conductor is equal to PØ Webbers.
- Time taken for one revolution is equal to 1/N min or 60/N sec

  Therefore rate of cutting of flux is equal to = dØ/dt

  = "PØ" / "60/N" (wb/sec) = PØN/60 (wb/sec)

  Since, f = PN/120 and 2f = PN/60 , then dØ/dt = 2Øf
- According to faraday's second law of Electro Magnetic Induction,
- The average value of the induced emf per conductor in each phase = 2fØ volts
- The average value of the induced emf per phase $=2fØZ_{ph}$ volts
- The average value of the induced emf per phase $=2fØ(2T_{ph})$ volts
- Therefore, RMS value of emf per phase = Form factor * Average Value

  $= 1.11*4fØT_{ph} = 4.44ØfT_{ph}$
- In a practical alternator the space distribution of the filed flux is not purely sinusoidal, it is having some distortion and moreover in a practical alternator short pitch winding is used, therefore by these two reasons, the actual EMF that is induced is somewhat less than the emf that is arrived at.
- Therefore by inserting pitch factor (or) chording factor (or) coil span factor (k_c or k_p) and Distribution or breadth factor (k_d or k_b) in the above emf equation , the actual emf equation is obtained and is given as
- RMS value of emf (E) per phase including the winding factor (k_w) is

$$E = 4.44ØfT_{ph}\, k_w = 4.44ØfT_{ph}\, k_c\, k_d$$

Winding Terminology

Pole pitch: Distance between two adjacent opposite main poles by the no. of armature conductors.

Coil span: Distance between two coils starting and ending conductors

The distance between any two conductors is called slot angle (β),

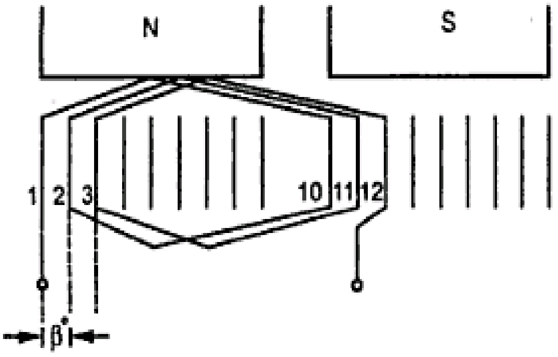
Short pitch angle (α) = short chorded slots × B

- If the distance b/w two coils sides of a coil, i.e. coil span is equal to one pole pitch, i.e. 180°E , it is called as full pitch winding.
- If the distance b/w two coils sides of a coil, i.e. coil span is less than one pole pitch i.e 180°E, it is called short pitch (or) fractional chorded winding.
- If the winding is short pitched by one slot then the short pitch angle α is equal to slot angle β.

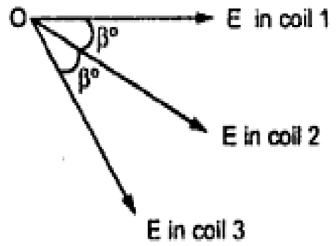
- If it is short pitched by two slots, then $\alpha = 2\beta$ and so on.

Pitch Factor (or) Chording Factor (or) Coil Span Factor

It is the ratio of vector sum of the emfs induced in the two coil sides of coil to their arithmetic sum .



(a) Distributed winding

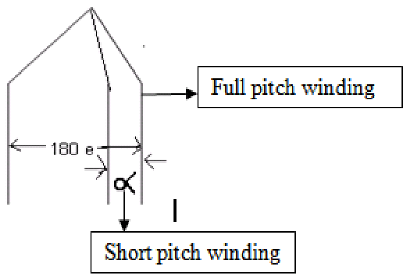


(b) Phase difference between induced e.m.f.

$$kc = \frac{\text{vector sum of induced emf per coil}}{\text{arthimetic sum of induced emf per coil}}$$

(or)

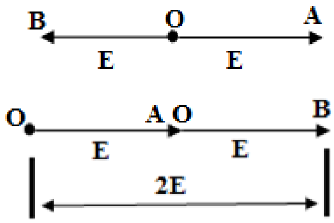
$$kc = \frac{\text{voltage induced in short pitch winding}}{\text{voltage induced in full pitch winding}}$$



Arithmetic sum:-

Let, The coil span of the short pitch winding is less than one pole pitch (180°) by an angle α.

The emf induced per coil side namely OA = E volts



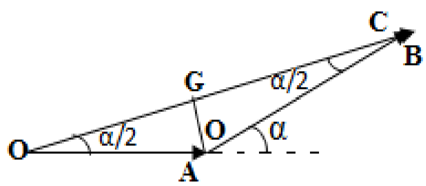
The emf induced in another coil side namely OB = E volts

Then, ***Arithmetic sum*** of emfs induced = OA + OB = **2E** volts

Vector sum:-

The emf induced per coil side namely OA = E volts

The emf induced in another coil side namely OB = E volts short pitched by α



Then, ***Vector sum*** of emfs induced is OC = OG + GC

From Δ OGA, OG = OA cos(α/2) = E cos(α/2) and

From Δ OGC, GC = OB cos(α/2) = E cos(α/2)

Therefore, ***Vector sum*** of emfs induced = OC = E cos(α/2) + E cos(α/2) = **2E cos(α/2)**

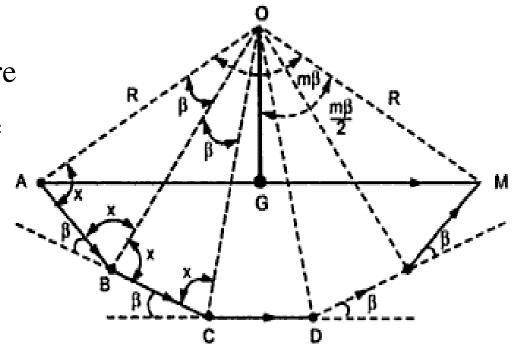
$$k_c = \frac{2E\cos\left(\frac{\alpha}{2}\right)}{2E} = \cos\left(\frac{\alpha}{2}\right) \Rightarrow k_c = \cos\left(\frac{\alpha}{2}\right)$$

Distribution Factor (or) breadth factor:- (k_d or k_b)

- The ratio of the vector sum of the e.m.fs induced in all the coils distributed in a number of slots under one pole to the arithmetic sum of the e.m.fs induced (or to the resultant of the e.m.fs induced in all the coils concentrated in one slot under one pole) is known as distributed factor k_d.

$$k_d = \frac{\text{vector sum of induced emf in all coils under one pole}}{\text{arthimetic sum of induced emf in all coils under the same pole}}$$

- It is the ratio of voltage induced in a distribution winding to the voltage induced in the concentric winding.



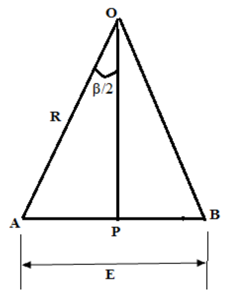
- Let 'm' be the no. of stator slots per pole per phase, where no. of slots per pole is defined as pole pitch (n), then m = n/3.
- The slot angle 'β' =180°/no.of slots/pole. $B=180^0 / n$

  Let,

  E = EMF induced per conductor.

  R = radius

  O = centre of the circle is drawn to pass through the points ABCD



- Arithmetic sum of emf induced in the conductors of 'm' no. of slots per pole per phase = m*E

  From Δ OAB, induced EMF AB = AP +PB

  In Δ OPA, AP = E/2 = R sin(β/2) and PB = E/2 = R sin(β/2)

  Therefore AB = induced emf E = 2R sin (β/2)

Arithmetic sum of emf induced in the conductors = 2mR sin (β/2)

- Vector sum of emf induced in the conductors of 'm' no. of slots per pole per phase = AM

  From Δ OAM,

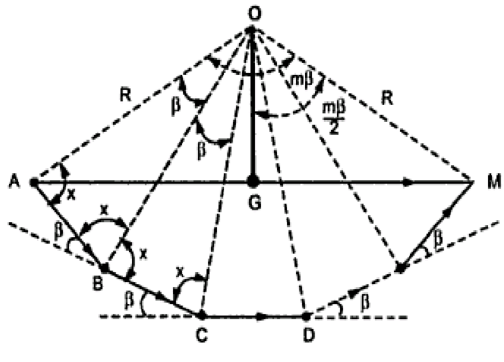
  Angle between OA and OM is mβ

  Drawing an perpendicular bisector of OG to AM, then

  AM = AG + GM (AG = GM)

  In a right angled triangle OGM,

  GM = AG = R Sin (mβ)/2



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Therefore,

AM = AG + GM =R Sin (mβ)/2+ R Sin (mβ)/2 = 2R Sin (mβ)/2

Vector sum of emf induced in the conductors = 2R Sin (mβ)/2

Thus, the distribution factor k_d is

$$k_d = \frac{2RSin\left(\frac{m\beta}{2}\right)}{2mRSin\left(\frac{\beta}{2}\right)} \Rightarrow K_d = \frac{Sin\left(\frac{m\beta}{2}\right)}{m\ Sin\left(\frac{\beta}{2}\right)}$$

Concentration Winding:

- Each coil side containing a no. of conductors, and if all the conductors of a coil side are placed in a single slot, it is called concentrated coil
- It gives more voltage but the sine wave will not be smooth

Distribution Winding:

- When the conductors of the coil side are distributed in different slots, it is called as distributed slots.
- It gives less voltage but the wave form will be smooth.

Advantages of Short Pitch Winding:

- Copper in end connection can be saved.
- Harmonics are reduced
- Iron losses will be reduced
- Efficiency will be increased
- Generated voltage waveform will be improved is more sinusoidal.

Disadvantages of Short Pitch Winding:

- The magnitude of the induced voltage will be reduced

VOLTAGE REGULATION OF ALTERNATOR:

- When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, and the amount of this variation determines the regulation of the machine.
- When the alternator is loaded the terminal voltage decreases as the drops in the machine stars increasing and hence it will always be different than the induced emf.
- Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when the load at a given power factor is removed without change in speed and excitation.

(or)

- The numerical value of the regulation is defined as the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged expressed as a percentage of rated voltage.

Hence regulation can be expressed as

$$\% \text{ Regulation } = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

where
E_{ph} = induced emf per phase,
V_{ph} = rated terminal voltage per phase

EMF method (or) Synchronous impedance method:

This method is also known as synchronous impedance method.

Here the magnetic circuit is assumed to be unsaturated.

In this method the MMFs (fluxes) produced by rotor and stator are replaced by their equivalent emf, and hence called emf method.

To predetermine the regulation by this method the following information is to be determined.

Open circuit characteristics of the alternator.

Short circuit characteristics of the alternator.

The voltage drop in an alternator is mainly due to the following reasons

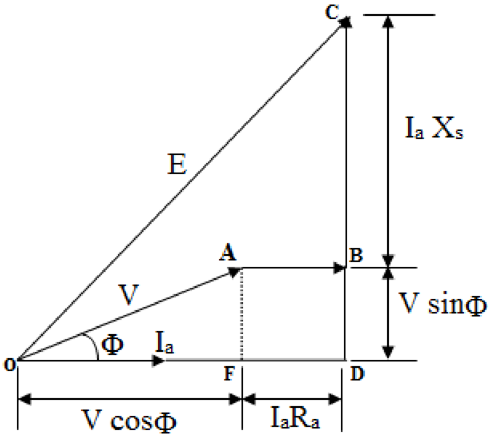
1. Voltage drop due to armature winding resistance ($I_a R_a$)
2. Voltage drop due to armature winding leakage reactance ($I_a X_L$)
3. Voltage drop due to armature reaction drop ($I_a X_a$)

- The combination of 2 and 3 leads to the voltage drop due to armature winding leakage reactance and armature reaction drop called as voltage drop due to synchronous reactance (X_s)= $I_a (X_L+X_a) = I_a X_s$
- Combination of the drops due to R_a and X_s is known as voltage drop due to synchronous impedance drop ($I_a Z_s$)

Calculation of no load induced emf (E) from the terminal voltage (V)

The calculation of no load induced emf (E) from the terminal voltage (V) at rated load depends on the nature of the load

For Lagging pf loads (inductive loads):



Let the known quantities are

V = Terminal voltage under rated load in Volts = OA

I_a = Rated armature current in Ampere

R_a = Armature resistance in ohms

X_s = synchronous reactance in ohms

E = No load induced emf in Volts = OC

From the KVL

$$\vec{E} = \vec{V} + I_a(R_a + jX_s)$$

1. Draw the phasor diagram for the above KVL equation as shown in the figure with known quantities
2. Take the reference phasor as OA = terminal voltage (V), since the load is inductive the current is lagging to phasor OA by its load phase angle Φ lag.
3. Add I_aR_a drop = AB = FD to the terminal voltage V which is inpase to I_a
4. From point B add I_aX_s drop = BC which is leading to I_a by 90^0
5. Join points O and C i.e OC = E no-load induced emf
6. From ΔODC

$$OC = \sqrt{OD^2 + DC^2} \quad \Rightarrow \mathrm{OD = OF + FD = Vcos\Phi + I_aR_a}$$

$$\Rightarrow \mathrm{DC = DB + BC = Vsin\,\Phi + I_aX_s}$$

$$E = \sqrt{(\mathrm{Vcos\Phi + I_aR_a})^2 + (\mathrm{Vsin\,\Phi + I_aX_s})^2} \quad \text{------ LAGGING PF}$$

For Unity pf loads (resistive loads):

Since phase angle Φ = 0 degrees, the power factor cosΦ = 1

Then from ΔOBC

$$OC = \sqrt{OB^2 + BC^2} \quad \Rightarrow \mathrm{OB = OA + AB = V + I_aR_a}$$

$$\Rightarrow \mathrm{BC = I_aX_s}$$

$$E = \sqrt{(V + \mathrm{I_aR_a})^2 + (\mathrm{I_aX_s})^2} \quad \text{----- UPF LOADS}$$

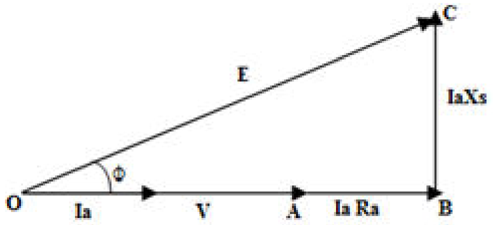
For Leading pf loads (capacitive loads):

From ΔODC

$OC = \sqrt{OD^2 + DC^2} \;\; \Rightarrow \; \mathrm{OD = OF + FD = Vcos\Phi + I_aR_a}$

$\Rightarrow \; \mathrm{DC = DB - BC = Vsin\,\Phi - I_aX_s}$

$E = \sqrt{(\mathrm{Vcos\Phi + I_aR_a})^2 + (\mathrm{Vsin\,\Phi - I_aX_s})^2}$ ------LEADING PF



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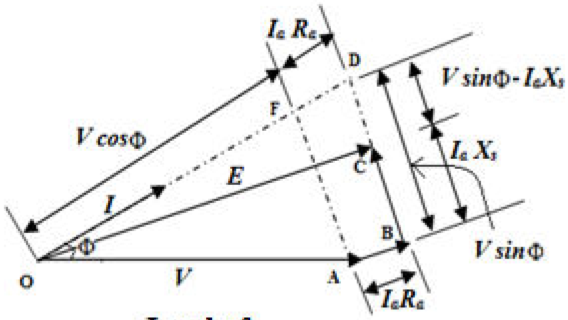


Lead pf

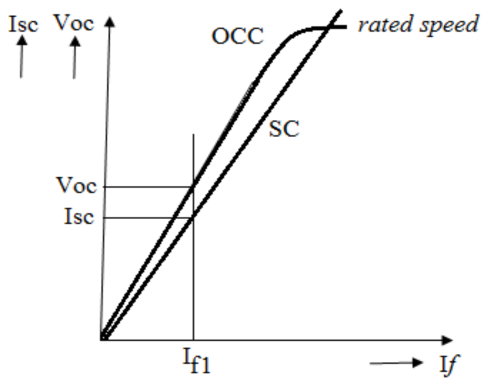
Open circuit characteristics on the alternator

1. The alternator is made to run at no-load or with the terminals kept ***opened.***
2. The alternator is operated with constant speed at rated value.
3. A voltmeter is connected in parallel to the opened terminals.
4. A variable excitation is applied to the field winding in a step wise.
5. As the voltage induced in the alternator is directly proportional to the excitation.
6. Tabulate the values of field currents and the corresponding induced voltages up to 125% of rated voltage.
7. Plot the graph between field current and open circuit voltage as shown in the below figure.
8. The open circuit characteristic is linear at the lower portion and is almost constant at the rated excitation values.

Short circuit characteristics on the alternator

1. The alternator is made to run with the terminals shorted
2. The alternator is operated with constant speed at rated value
3. An ammeter is connected in series to the shorted terminals.
4. An excitation is applied to the field winding such a way that rated short circuited current passes through it
5. As the current in the alternator under short circuit is directly proportional to the excitation, so the plot of the Short circuit characteristic is a straight line passing through the origin.

Calculation of synchronous impedance of an alternator:



1. From the plots of OCC and SC, V_{oc} and I_{sc} corresponding to the field current of I_{f1} is identified and the ratio of these V_{oc} to I_{sc} is defined as the synchronous impedance Z_s.

   $$Z_s = \frac{V_{oc} \text{ at } I_{fl}}{I_{sc} \text{ at same } I_{fl}}$$

2. From the obtained synchronous impedance Z_s, the synchronous reactance X_s is calculated with the known value of armature resistance R_a

   $$Z_s = \sqrt{R_a^2 + X_s^2} \quad \Rightarrow X_s = \sqrt{Z_s^2 - R_a^2}$$

3. Due to this synchronous impedance Z_s there is a fall in terminal voltage when the load on the alternator is increased from no load to rated load.
4. The difference of the voltage from no-load (E) to rated load (V) expressed in terms of rated voltage (V) is known as voltage regulation

   $$\% \text{ Regulation} = \frac{E - V}{V} \times 100$$

   Where
   E = No-load voltage in Volts
   V = Rated load Voltage in Volts
5. The no-load voltage E is calculated using the above defined formula after obtaining the value of X_s from point no.2
6. The formula for no-load voltage E is

$$E = \sqrt{(V\cos\Phi + I_a R_a)^2 + (V\sin\Phi \pm I_a X_s)^2}$$

(+) Sign is for lagging power factor and (-) Sign is for leading power factor.

Since the regulation is estimated from the calculation of EMF value hence method is known as ***EMF method*** or from the calculation of synchronous impedance value hence called ***synchronous impedance method***

Synchronous Motors: Construction of three phase synchronous motor - operating principle –equivalent circuit of synchronous motor.

INTRODUCTION

- It may be recalled that a d.c. generator can be run as a d.c. motor. In like manner, an alternator may operate as a motor by connecting its armature winding to a 3-phase supply. It is then called a synchronous motor.
- As the name implies, the synchronous motor runs at synchronous speed (Ns = 120f/P) i.e., in synchronism with the revolving field produced by the 3-phase supply.
- The speed of rotation is, therefore, tied to the frequency of the source. Since the frequency is

fixed, the motor speed stays constant irrespective of the load or voltage of 3- phase supply.

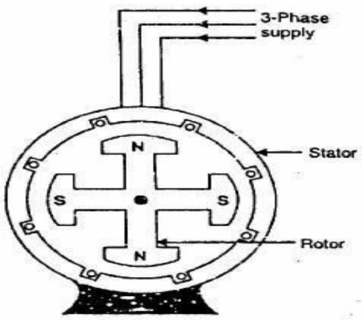
- However, synchronous motors are not used so much because they run at constant speed (i.e., synchronous speed) but because they possess other unique electrical properties.

CONSTRUCTION

- A synchronous motor is a machine that operates at synchronous speed and converts electrical energy into mechanical energy.
- It is fundamentally an alternator operated as a motor. Like an alternator, a synchronous motor has the following two parts:

i. Stator which houses 3-phase armature winding in the slots of the stator core and receives power from a 3-phase supply

ii. Rotor that has a set of salient poles excited by DC to form alternate N and S poles.



- The exciting coils located on the rotor shaft are connected in series to two slip rings and DC is fed into the winding from an external exciter mounted on the same shaft.
- The stator is wound for the same number of poles as the rotor poles and its speed of rotation is given
- Synchronous speed $N_s = \frac{120f}{p}$

  Where, f = frequency of supply in Hz

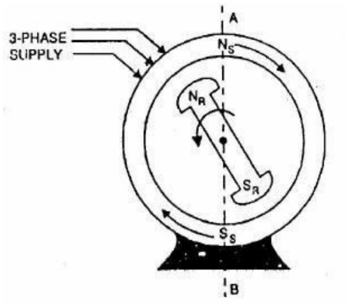
  p = number of poles
- An important drawback of a synchronous motor is that it is not self-starting and auxiliary means have to be used for starting it.

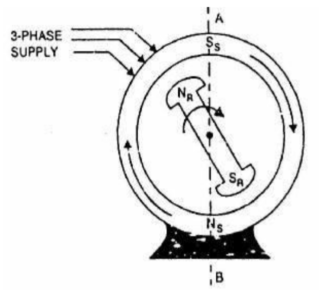
<u>Salient features of a synchronous motor:</u>

1. Synchronous motor runs only at synchronous speed or it doesn't runs at all.
2. Its speed is constant (synchronous speed) at all loads.
3. Synchronous motor can be made to operate over a wide range of power factors (lagging, unity or leading) by adjustment of its field excitation. Therefore, a synchronous motor can be made improve the power factor of the system.
4. Synchronous motors are generally of the salient pole type.
5. Synchronous motor is not self-starting and an auxiliary means has to be used for starting it.

OPERATING PRINCIPLE

- The fact that a synchronous motor has no starting torque can be easily explained.
- Consider a 3-phase synchronous motor having two rotor poles NR and SR. Then the stator will also be wound for two poles NS and SS.
- The motor has direct voltage applied to the rotor winding and a 3-phase voltage applied to the stator winding.

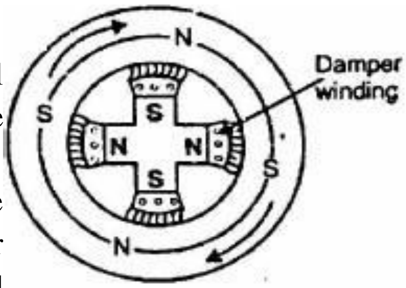




- The stator winding produces a rotating field which revolves round the stator at synchronous speed Ns(= 120 f/P).
- The direct (or zero frequency) current sets up a two-pole field which is stationary so long as the rotor is not running.
- Thus, we have a situation in which there exists a pair of revolving armature poles (i.e., NS - SS) and a pair of stationary rotor poles (i.e., NR - SR).
- Suppose at any instant, the stator poles are at positions A and B as shown in figure below, It is clear that poles NS and NR repel each other and so do the poles SS and SR.
- Therefore, the rotor tends to move in the anticlockwise direction. After a period of half-cycle (or ½ f = 1/100 second), the polarities of the stator poles are reversed but the polarities of the rotor poles remain the same as shown in below figure Now SS and NR attract each other and so do NS and SR.
- Therefore, the rotor tends to move in the clockwise direction. Since the stator poles change their polarities rapidly, they tend to pull the rotor first in one direction and then after a period of half-cycle in the other. Due to high inertia of the rotor, the motor fails to start.
- Hence, the synchronous motor has no self-starting torque i.e., a synchronous motor cannot start by itself.

<u>Making Synchronous Motor Self-Starting</u>

- A synchronous motor cannot start by itself. In order to make the motor self-starting, a squirrel cage winding (also called damper winding) is provided on the rotor.



- The damper winding consists of copper bars embedded in the pole faces of the salient poles of the rotor as shown in Fig.
- The bars are short-circuited at the ends to form in effect a partial squirrel cage winding. The damper winding serves to start the motor.
- To start with, 3-phase supply is given to the stator winding while the rotor field winding is left unenergized. The rotating stator field induces currents in the damper or squirrel cage winding and the motor starts as an induction motor.
- As the motor approaches the synchronous speed, the rotor is excited with direct current. Now the resulting poles on the rotor face poles of opposite polarity on the stator and a strong magnetic attraction is set up between them. The rotor poles lock in with the poles of rotating flux. Consequently, the rotor revolves at the same speed as the stator field i.e., at synchronous speed.
- Because the bars of squirrel cage portion of the rotor now rotate at the same speed as the rotating stator field, these bars do not cut any flux and,
- Therefore, have no induced currents in them. Hence squirrel cage portion of the rotor is, in effect, removed from the operation of the motor.
- It may be emphasized here that due to magnetic interlocking between the stator and rotor poles, a synchronous motor can only run at synchronous speed. At any other speed, this magnetic interlocking (i.e., rotor poles facing opposite polarity stator poles) ceases and the average torque becomes zero. Consequently, the motor comes to a halt with a severe disturbance on the line.

  Note: It is important to excite the rotor with direct current at the right moment.

  For example, if the d.c. excitation is applied when N-pole of the stator faces N pole of the rotor, the resulting magnetic repulsion will produce a violent mechanical shock. The motor will immediately slow down and the circuit breakers will trip. In practice, starters for synchronous motors are designed to detect the precise moment when excitation should be applied.

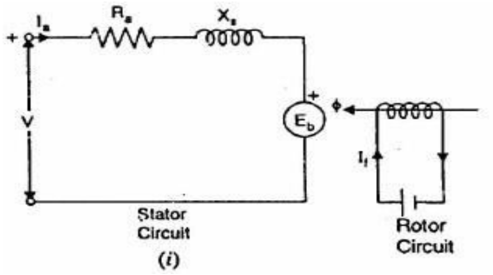
EQUIVALENT CIRCUIT OF SYNCHRONOUS MOTOR

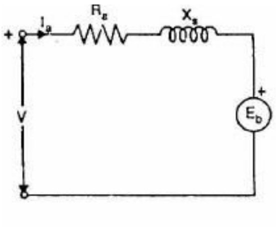
Unlike the induction motor, the synchronous motor is connected to two electrical systems;

i. DC source to the rotor terminals
ii. AC source to the stator terminals

1. Under normal conditions of synchronous motor operation, no voltage is induced in the rotor by the stator field because the rotor winding is rotating at the same speed as the stator field.

2. In the stator winding, two effects are to be considered, the effect of stator field on the stator winding and the effect of the rotor field cutting the stator conductors at synchronous speed.





i. The first effect of stator field on the stator (or armature) conductors is accounted for by including an inductive reactance in the armature winding. This is called synchronous reactance X_s. A resistance R_a must be considered to be in series with this reactance to account for the copper losses in the stator or armature winding. This resistance combines with synchronous reactance and gives the synchronous impedance of the machine.

ii. The second effect is that a voltage is generated in the stator winding by the synchronously-revolving field of the rotor. This generated e.m.f. Eb is known as back e.m.f. and opposes the stator voltage V. The magnitude of Eb depends upon rotor speed and rotor flux per pole. Since rotor speed is constant; the value of Eb depends upon the rotor flux per pole i.e. exciting rotor current I_f.

Above fig. shows the schematic diagram for one phase of a star-connected synchronous motor. Referring to the equivalent circuit,

Net voltage per phase in stator winding is Er = V - Eb

Armature current per phase in stator winding is $I_a = \frac{E_r}{Z_s} = \frac{V - E_b}{\sqrt{R_a^2 + X_s^2}}$

A synchronous motor is said to be

Normally excited if the field excitation is such that $E_b = V$

Under-excited if the field excitation is such that $E_b < V$

Over-excited if the field excitation is such that $E_b > V$

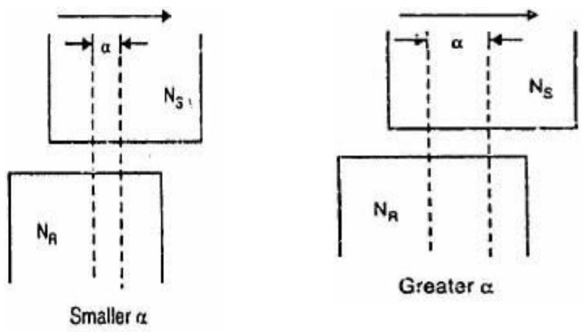
- As we shall see, for both normal and under excitation, the motor has lagging power factor. However, for over-excitation, the motor has leading power factor.

  Note: In a synchronous motor, the value of Xs is 10 to 100 times greater than Ra. Consequently, we can neglect Ra unless we are interested in efficiency or heating effects.

MOTOR ON LOAD

- In d.c. motors and induction motors, an addition of load causes the motor speed to decrease. The decrease in speed reduces the counter e.m.f. enough so that additional current is drawn from the source to carry the increased load at a reduced speed. This action cannot take place in a synchronous motor because it runs at a constant speed (i.e., synchronous speed = 3000 rpm) at all loads.

- Whereas when the mechanical load on synchronous motor is increased the rotor poles fall slightly behind the stator poles while continuing to run at 2990 r.p.m synchronous speed. The angular displacement between stator and rotor poles (called torque angle α) causes the phase of back e.m.f. E_b to change w.r.t. supply voltage V. This increases the net e.m.f. E_r in the stator winding. Consequently, stator current Ia (= Er/Zs) increases to carry the load.



The following points may be noted in synchronous motor operation:

1. A synchronous motor runs at synchronous speed at all loads. It meets the increased load not by a decrease in speed but by the relative shift between stator and rotor poles i.e., by the adjustment of torque angle α.
2. If the load on the motor increases, the torque angle α also increases (i.e., rotor poles lag behind the stator poles by a greater angle) but the motor continues to run at synchronous speed. The increase in torque angle α causes a greater phase shift of back e.m.f. Eb w.r.t. supply voltage V. This increases the net voltage Er in the stator winding. Consequently, armature current Ia (= Er/Zs) increases to meet the load demand.
3. If the load on the motor decreases, the torque angle a also decreases. This causes a smaller phase shift of Eb w.r.t. V. Consequently, the net voltage Er in the stator winding decreases and so does the armature current Ia (=Er/Zs).

<u>Pull-Out Torque</u>

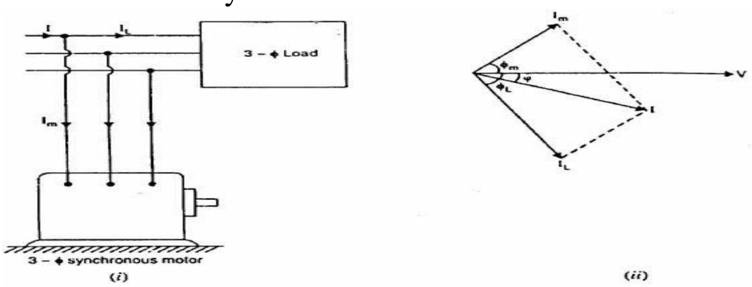
- There is a limit to the mechanical load that can be applied to a synchronous motor. As the load increases, the torque angle α also increases so that a stage is reached when the rotor is pulled out of synchronism and the motor comes to a standstill.
- This load torque at which the motor pulls out of synchronism is called pull—out or breakdown torque. Its value varies from 1.5 to 3.5 times the full— load torque.

SYNCHRONOUS CONDENSER

- A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor.
- An over-excited synchronous motor running on no-load in known as synchronous condenser.
- When such a machine is connected in parallel with induction motors or other devices that operate at low lagging power factor, the leading kVAR supplied by the synchronous condenser partly neutralizes the lagging reactive kVAR of the loads. Consequently, the power factor of the system is improved.
- Fig. below shows the power factor improvement by synchronous condenser method. The 3 - Φ load takes current I_L at low lagging power factor cos Φ_L. The synchronous condenser takes a current I_m which leads the voltage by an angle Φ_m. The resultant current I is the vector sum of I_m and I_L and lags behind the voltage by an angle Φ. It is clear that Φ is less than Φ_L so that cos Φ is greater than cos Φ_L. Thus the power factor is increased from cos Φ_L to cos Φ. Synchronous condensers are generally used at major bulk supply substations for power factor improvement

Advantages

1. By varying the field excitation, the magnitude of current drawn by the motor can be changed by any amount. This helps in achieving step less control of power factor.
2. The motor windings have high thermal stability to short circuit currents.
3. The faults can be removed easily.



Disadvantages

1. There are considerable losses in the motor.
2. The maintenance cost is high.
3. It produces noise.
4. Except in sizes above 500 RVA, the cost is greater than that of static capacitors of the same rating.
5. As a synchronous motor has no self-starting torque, then-fore, an auxiliary equipment has to be provided for this purpose.

Applications of Synchronous Motors

1. Synchronous motors are particularly attractive for low speeds (< 300 r.p.m.) because the power factor can always be adjusted to unity and efficiency is high.
2. Overexcited synchronous motors can be used to improve the power factor of a plant while carrying their rated loads.
3. They are used to improve the voltage regulation of transmission lines.

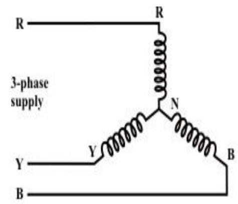
Unit – 4 (BEE) R19&R20 Regulations – I ECE II Semester

Induction Machine: Principle of operation and construction of three-phase induction motors –slip ring and squirrel cage motors – slip-torque characteristics – efficiency calculation – starting methods Brake test on 3-Phase Induction Motor.

CONSTRUCTION OF 3-PHASE INDUCTION MOTOR

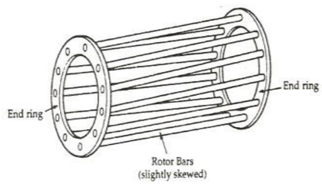
The 3-Phase induction motor consists of mainly two parts namely stator and rotor

Stator: The stator consists of



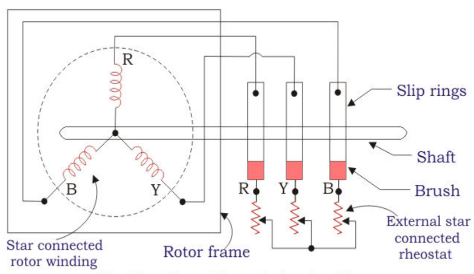
- ***Stator frame:*** The stator frame is made of cast iron and consists of cooling fins
  It gives the support and protects other parts of the motor
- ***Stator core:*** The stator core is made of with laminated high grade alloy steel stampings and slotted on the inner periphery and these stampings are insulated.
- ***Stator winding:*** The stator winding is placed in the stator core, which is connected either in star or delta

Squirrel cage Rotor:



1. The rotor core is a cylindrical one built from a high grade alloy steel laminations.
2. It consists of rotor slots in parallel to the shaft axis on the outer periphery.
3. In general the slots are not parallel to the shaft but skewed with some angle to the shat
4. The purpose of the skewing is to prevent interlocking and to reduce the humming noise
5. The rotor copper bars are placed in the rotor slots and the bars are short circuited with end rings.
6. In Cage rotor type there is no chance of adding the external resistance to the rotor to improve the torque developed at starting.

- **Slip ring rotor (or) Phase Wound rotor:**



Slip Ring Three Phase Induction Motor

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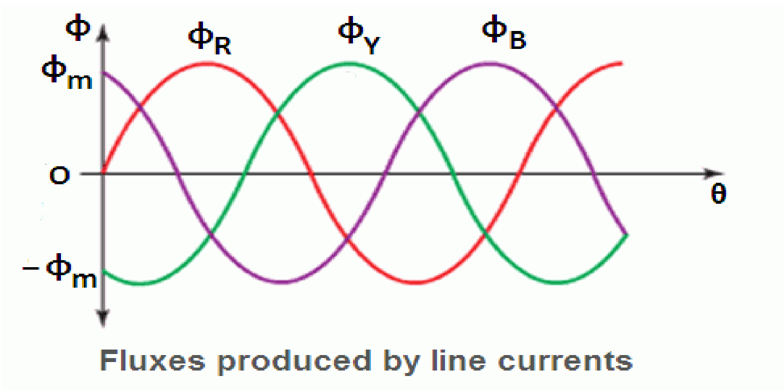
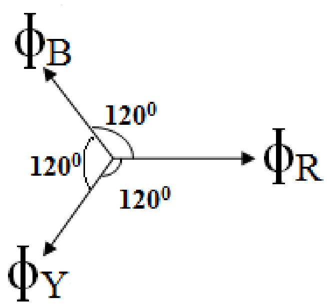
1. The rotor core is a cylindrical one built from a high grade alloy steel laminations.
2. It consists of rotor slots on the outer periphery where the star connected winding is done.
3. The star connected rotor winding is done for the same poles as that of the stator winding
4. The ends of the star connected rotor winding are connected to the three slip rings placed on the shaft.
5. The carbon brushes are mounted on the slip rings, through which an external resistance is added to the rotor.
6. The advantage of the Wound rotor is the starting torque is improved by adding the external resistance to the rotor using slip rings.

Rotating Magnetic Field

1. The induction motor rotates due to the **rotating magnetic field in 3 phase induction motor**, which is produced by the stator winding in the air gap between in the stator and the rotor.
2. The stator has a three phase stationary winding which can be either star connected or delta connected.
3. Whenever the AC supply is connected to the stator windings, line currents I_R, I_Y, and I_B start flowing.
4. These line currents have phase difference of 120^o with respect to each other.
5. Due to each line current, a sinusoidal flux is produced in the air gap.
6. These fluxes have the same frequency as that of the line currents, and they also have the same phase difference of 120^o with respect to each other.

Let the flux produced by the line currents I_R, I_B, I_Y be φ_R, φ_B, φ_Y respectively.





Mathematically, they are represented as follows:

$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta$
$\varphi_Y = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (\theta - 120^o)$
$\varphi_B = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (\theta - 240^o)$

The effective or total flux (ϕ_T) in the air gap is equal to the phasor sum of the three components of fluxes ϕ_R, ϕ_Y and, ϕ_B.

Therefore, $\phi_T = \phi_R + \phi_Y + \phi_B$

Step 1: The values of total flux ϕ_T for different values of θ such as 0, 60, 120 , 180 ….. 360°. are to be calculated

Step 2: For every value of θ in step 1, draw the phasor diagram, with the phasor ϕ_R as the reference phasor i.e. all the angles are drawn with respect to this phasor.

For θ = 0°

$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta = 0$

$\varphi_Y = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (\theta - 120^o) = \varphi_m \sin (0 - 120^o) = (-)\varphi_m \sin 120^o = -0.866\ \varphi_m$

$\varphi_B = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (\theta - 240^o) = \varphi_m \sin (0 - 240^o) = (-)\varphi_m \sin 240^o = 0.866\ \varphi_m$

Therefore, $\phi_T = 0 + \phi_Y + \phi_B = \phi_T = 0 + (-\phi_Y) + \phi_B$

$$\Phi_T = \sqrt{(\Phi_Y)^2 + (\Phi_B)^2 + 2\Phi_Y\Phi_B \cos 60}$$

$$\Phi_T = \sqrt{\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + 2\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\frac{1}{2}}$$

$$\Phi_T = \sqrt{3\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2} = \frac{3}{2}\varphi_m = 1.5\varphi_m$$

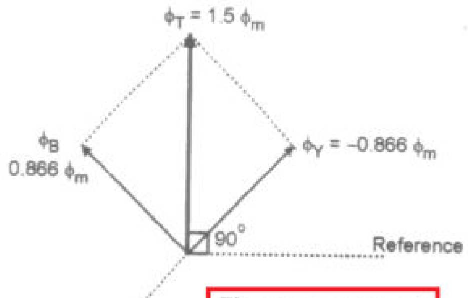
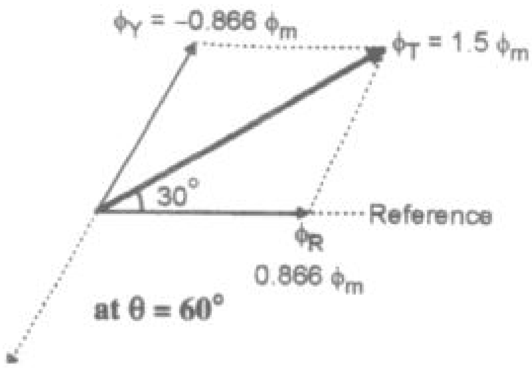


Fig. (a) : ϕ_T at θ = 0°



at θ = 60°

For θ = 60°

$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta = \varphi_m \sin 60 = 0.866\ \varphi_m$

$\varphi_Y = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (\theta - 120^o) = \varphi_m \sin (60 - 120^o) = (-)\varphi_m \sin 60^o = -0.866\ \varphi_m$

$\varphi_B = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (\theta - 240^o) = \varphi_m \sin (60 - 240^o) = (-)\varphi_m \sin 180^o = 0$

Therefore, $\phi_T = \phi_R + (-\phi_Y) + 0$

$$\Phi_T = \sqrt{(\Phi_R)^2 + (\Phi_Y)^2 + 2\Phi_Y\Phi_R \cos 60}$$

3

$$\Phi_T = \sqrt{\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + 2\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\frac{1}{2}}$$

$$\Phi_T = \sqrt{3\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2} = \frac{3}{2}\varphi_m = 1.5\varphi_m$$

For $\theta = 120^0$

$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta = \varphi_m \sin 120 = 0.866\ \varphi_m$
$\varphi_Y = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (120 - 120^o) = (-)\varphi_m \sin 0^o = 0$
$\varphi_B = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (120 - 240^o) = (-)\varphi_m \sin 120^o = -0.866\ \varphi_m$

Therefore, $\phi_T = \phi_R + 0 + (-\phi_B)$

$$\Phi_T = \sqrt{(\Phi_R)^2 + (\Phi_B)^2 + 2\Phi_R\Phi_B\cos 60}$$

$$\Phi_T = \sqrt{\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + 2\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\frac{1}{2}}$$

$$\Phi_T = \sqrt{3\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2} = \frac{3}{2}\varphi_m = 1.5\varphi_m$$

For $\theta = 180^0$

$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta = \varphi_m \sin 180 = 0$
$\varphi_Y = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (180 - 120^o) = \varphi_m \sin 60^o = 0.866\ \varphi_m$
$\varphi_B = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (180 - 240^o) = (-)\varphi_m \sin 60^o = -0.866\ \varphi_m$

Therefore, $\phi_T = 0 + \phi_Y + (-\phi_B)$

$$\Phi_T = \sqrt{(\Phi_Y)^2 + (\Phi_B)^2 + 2\Phi_Y\Phi_B\cos 60}$$

$$\Phi_T = \sqrt{\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + 2\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\frac{1}{2}}$$

$$\Phi_T = \sqrt{3\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2} = \frac{3}{2}\varphi_m = 1.5\varphi_m$$

For $\theta = 240^0$

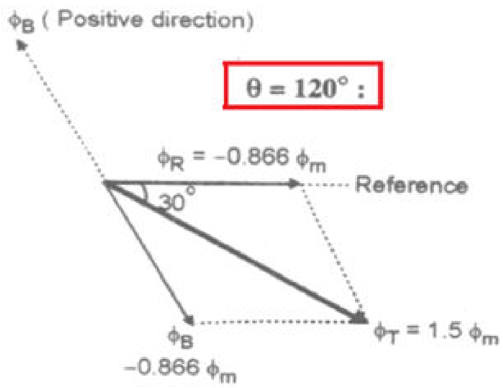
$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta = \varphi_m \sin 240 = -0.866\ \varphi_m$
$\varphi_Y = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (240 - 120^o) = \varphi_m \sin 120^o = 0.866\ \varphi_m$
$\varphi_B = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (240 - 240^o) = \varphi_m \sin 0^o = 0$

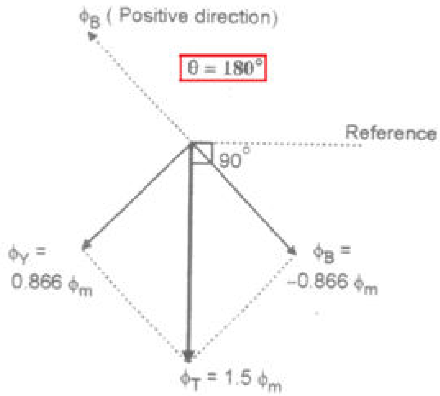
Therefore, $\phi_T = (-\phi_R) + \phi_Y + 0$

$$\Phi_T = \sqrt{(\Phi_R)^2 + (\Phi_Y)^2 + 2\Phi_R\Phi_Y\cos 60}$$

$$\Phi_T = \sqrt{\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + 2\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\frac{1}{2}}$$

$$\Phi_T = \sqrt{3\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2} = \frac{3}{2}\varphi_m = 1.5\varphi_m$$





For θ = 300⁰

$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta = \varphi_m \sin 300 = -0.866\ \varphi_m$

$\varphi_Y = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (300 - 120^o) = \varphi_m \sin 180^o = 0$

$\varphi_B = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (300 - 240^o) = \varphi_m \sin 60^o = 0.866\ \varphi_m$

Therefore, $\phi_T = (-\phi_R) + \phi_Y + 0$

$$\Phi_T = \sqrt{(\Phi_R)^2 + (\Phi_B)^2 + 2\Phi_R\Phi_B \cos 60}$$

$$\Phi_T = \sqrt{\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + 2\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\frac{1}{2}}$$

$$\Phi_T = \sqrt{3\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2} = \frac{3}{2}\varphi_m = 1.5\varphi_m$$

For θ = 360⁰

$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta = \varphi_m \sin 360 = 0$

$\varphi_Y = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (360 - 120^o) = \varphi_m \sin 240^o = -\ 0.866\ \varphi_m$

$\varphi_B = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (300 - 240^o) = \varphi_m \sin 60^o = 0.866\ \varphi_m$

Therefore, $\phi_T = 0 + (-\phi_Y) + \phi_B$

$$\Phi_T = \sqrt{(\Phi_Y)^2 + (\Phi_B)^2 + 2\Phi_Y\Phi_B \cos 60}$$

$$\Phi_T = \sqrt{\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + 2\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)\times\frac{1}{2}}$$

$$\Phi_T = \sqrt{3\times\left(\frac{\sqrt{3}}{2}\varphi_m\right)^2} = \frac{3}{2}\varphi_m = 1.5\varphi_m$$

In the similar way as shown in the phasor diagrams the resultant or total flux rotates 60 degrees for every instant and completes one cycle of rotation in the direction of phase sequence of the supply.

Thus when a three phase supply is applied to the three phase winding connected either in star or delta it produces a rotating magnetic field having

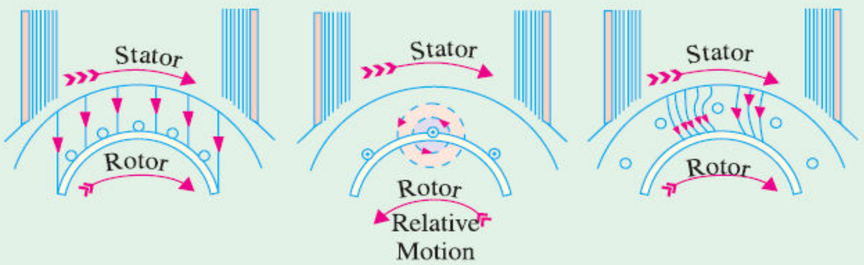
- *i.* ***a constant magnitude of 1.5 times the Φ_m***
- *ii.* ***a constant speed of synchronous speed N_s=120f/P***
- *iii.* ***a direction equal to its phase sequence***

WORKING PRINCIPLE OF 3-PHASE INDUCTION MOTOR

1. The balanced three-phase winding of the stator is supplied with a balanced three-phase voltage.
2. The current in the stator winding produces a rotating magnetic field, with constant magnitude of $1.5Ø_m$ and rotates at synchronous speed of N_s=120f/P
3. The magnetic flux lines in the air gap cut both stator and rotor (being stationary, as the motor speed is zero) conductors at the same speed.
4. The emfs in both stator and rotor conductors are induced at the same frequency, i.e. line or supply frequency, with No. of poles for both stator and rotor windings (assuming wound one) being same.
5. As the rotor winding is short-circuited at the slip-rings, current flows in the rotor windings.
6. The electromagnetic torque in the motor is in the same direction as that of the rotating magnetic field, due to the interaction between the rotating flux produced in the air gap by the current in the stator winding, and the current in the rotor winding.
7. This is as per Lenz's law, as the developed torque is in such direction that it will oppose the cause, which results in the current flowing in the rotor winding.
8. As the rotor starts rotating in the same direction, as that of the rotating magnetic field due to production of the torque as stated earlier, the relative velocity decreases, along with lower values of induced emf and current in the rotor.
9. If the rotor speed is equal that of the rotating magnetic field, which is termed as synchronous speed, and also in the same direction, the relative velocity is zero, which causes both the induced emf and current in the rotor to be reduced to zero. Under this condition, torque will not be produced.
10. So, for production of positive (motoring) torque, the rotor speed must always be lower than the synchronous speed. The rotor speed is never equal to the synchronous speed in an IM.

The setting up of the torque for rotating the rotor is explained below :

In Fig (a) is shown the stator field which is assumed to be rotating clockwise. The relative motion of the rotor with respect to the stator is *anticlockwise*. By applying Right-hand rule, the direction of the induced e.m.f. in the rotor is found to be outwards. Hence, the direction of the flux due to rotor current *alone*, is as shown in Fig. (b). Now, by applying the Left-hand rule, or by the effect of combined field [Fig. (c)] it is clear that the rotor conductors experience a force tending to rotate them in clockwise direction. Hence, the rotor is set into rotation in the same direction as that of the stator flux (or field).



(a) (b) (c)

Slip

It is defined as the relative speed or slip speed (N_s - N_r) expressed in terms of synchronous speed

$$s = \frac{N_S - N_r}{N_s}$$

- Since the speed at standstill is zero, the slip is 1.
- As the speed of rotor increases the slip decreases.

EFFECT OF ROTOR QUANTITIES WITH RESPECT TO THE SLIP IN A 3-PHASE INDUCTION MOTOR

The rotor quantities that effect with slip are

1. Rotor induced emf (E_r)
2. rotor emf's frequency (f_r)
3. induced currents (I_r)
4. rotor power factor ($\cos\Phi_r$)

Rotor induced emf

Under running conditions the induced emf is directly proportional to the relative speed (N_s-N_r)

E_2 at standstill = K N_s,

E_r at running = K (N_s-N_r)

$$\frac{E_r}{E_2} = \frac{N_S - N_r}{N_s} = s$$

Therefore $E_r = sE_2$

Rotor emf's frequency

Frequency of rotor emf at stand still $f_2=PN_s/120$

Frequency of rotor emf at running $f_r=P(N_s-N_r)/120$

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$$\frac{f_r}{f_2} = \frac{N_S - N_r}{N_s} = s$$ Therefore $f_r = sf_2 = sf$

Rotor reactance

Rotor reactance at stand still $X_2 = 2\Pi f L_2$

Rotor reactance at running $X_r = 2\Pi f_r L_2$

$$\frac{X_r}{X_2} = \frac{2\pi f_r L_2}{2\pi f_2 L_2} = \frac{f_r}{f_2} = \frac{sf_2}{f_2} = s$$ Therefore $X_r = sX_2$

Rotor impedance

Rotor impedance at stand still $Z_2 = R_2 + jX_2$

Rotor impedance at running $Z_r = R_2 + jX_r$

$$Z_2 = \sqrt{R_2^2 + X_2^2} \quad \text{and} \quad Z_r = \sqrt{R_2^2 + X_r^2} = \sqrt{R_2^2 + (sX_2)^2}$$

Rotor induced currents

The rotor current is defined as the ratio of the rotor emf to the rotor impedance.
Rotor current at stand still is

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{r_2^2 + x_2^2}}$$

Rotor current at running is

$$I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{r_2^2 + (s^2 x_2^2)}}$$

Rotor power factor

Power factor is defined as the ratio of the rotor resistance to the rotor impedance
Rotor power factor at stand still is

$$\cos\phi_2 = \frac{r_2}{Z_2} = \frac{r_2}{\sqrt{r_2^2 + x_2^2}}$$

Rotor power factor at running is

$$\cos\phi_r = \frac{r_2}{Z_r} = \frac{r_2}{\sqrt{r_2^2 + (s^2 x_2^2)}}$$

TORQUE EQUATION OF 3-Φ INDUCTION MOTOR

Torque at stand still

The torque in the motor is directly proportional to the product of flux and active component of the rotor current

$$T \,\alpha\, \phi\, I_2 \cos\phi_2$$

Here the flux is directly proportional to the rotor induced emf E_2 i.e $\phi \,\alpha\, E_2$

The rotor current I_2 and rotor power factor $\cos\Phi_2$ are

$$I_2 = \frac{E_2}{Z_2} \text{ and } \cos\phi_2 = \frac{R_2}{Z_2}$$

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$$T \,\alpha\, E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$T = k\frac{E_2^2 R_2}{R_2^2 + X_2^2} \quad \text{where} \quad k = \frac{3}{2\pi n_s} \quad \text{here } n_s \text{ is synchronous speed in rps}$$

Therefore, torque at standstill is $T = \left(\frac{3}{2\pi n_s}\right)\frac{E_2^2 R_2}{R_2^2 + X_2^2}$

From the above equation torque at stand still depends on rotor resistance (R_2), so keeping this R_2 as variable the condition for the maximum torque at standstill is

$$\frac{dT_{st}}{dR_2} = 0$$

Rewriting the stand still torque

$$T = K\frac{R_2}{R_2^2 + X_2^2} \quad \text{where } K = \frac{3E_2^2}{2\pi n_s} \quad \text{and} \quad T \,\alpha\, \frac{R_2}{R_2^2 + X_2^2}$$

$$\frac{d\left(\frac{R_2}{R_2^2 + X_2^2}\right)}{dR_2} = 0 \quad \Rightarrow \frac{\left(R_2^2 + X_2^2\right) - R_2\left(2R_2\right)}{\left(R_2^2 + X_2^2\right)^2} = 0 \quad \Rightarrow \left(R_2^2 + X_2^2\right) - R_2\left(2R_2\right) = 0$$

$$R_2^2 + X_2^2 = 2R_2^2 \;\Rightarrow\; R_2^2 = X_2^2 \quad \Rightarrow R_2 = X_2$$

Therefore on adding the resistance to the rotor such that $R_2 = X_2$, the motor will develop maximum torque at stand still.

The maximum torque at standstill is $T_{max} = \left(\frac{3}{2\pi n_s}\right)\frac{E_2^2 X_2}{X_2^2 + X_2^2} = \frac{K}{2X_2}$ $\quad T_{max} = \frac{3}{2\pi n_s}\frac{E_2^2}{2X_2}$

Torque at running condition

The torque in the motor is directly proportional to the product of flux and active component of the rotor current

$$T \,\alpha\, \phi\, I_r \cos\phi_r$$

Here the flux is directly proportional to the rotor induced emf E_2 i.e $\phi \,\alpha\, E_2$

The rotor current I_r and rotor power factor $\cos\Phi_r$ are

$$I_r = \frac{E_r}{Z_r} \text{ and } \cos\phi_r = \frac{R_2}{Z_r}$$

$$T \,\alpha\, E_2 \times \frac{E_r}{\sqrt{R_2^2 + X_r^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_r^2}}$$

$$T \,\alpha\, E_2 \times \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$T = k\frac{sE_2^2R_2}{R_2^2 + (sX_2)^2} \quad \text{where} \quad k = \frac{3}{2\pi n_s} \quad \text{here } n_s \text{ is synchronou s speed in rps}$$

Therefore, torque at standstill is $T = \left(\frac{3}{2\pi n_s}\right)\frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$

From the above equation torque under running condition depends on slip (s), so keeping this 's' as variable the condition for the maximum torque at running is

$$\frac{dT}{ds} = 0$$

Rewriting the torque under running

$$T = K\frac{sR_2}{R_2^2 + (sX_2)^2} \quad \text{where } K = \frac{3E_2^2}{2\pi n_s} \quad \text{and} \quad T\,\alpha\,\frac{sR_2}{R_2^2 + (sX_2)^2}$$

$$\frac{d\left(\frac{sR_2}{R_2^2 + (sX_2)^2}\right)}{ds} = 0 \quad \Rightarrow \frac{\left(R_2^2 + (sX_2)^2\right)R_2 - sR_2\left(2sX_2^2\right)}{\left(R_2^2 + (sX_2)^2\right)^2} = 0 \quad \Rightarrow \left(R_2^2 + (sX_2)^2\right)R_2 - sR_2\left(2sX_2^2\right) = 0$$

$$\left(R_2^2 + (sX_2)^2\right) = s\left(2sX_2^2\right) \quad \Rightarrow R_2^2 + (sX_2)^2 = 2s^2X_2^2 \quad \Rightarrow R_2^2 = (sX_2)^2 \quad \Rightarrow R_2 = (sX_2) \Rightarrow s_m = \frac{R_2}{X_2}$$

Therefore the motor when rotates at a slip $s_m = \frac{R_2}{X_2}$ then the motor will develop maximum torque at running.

The maximum torque at running is

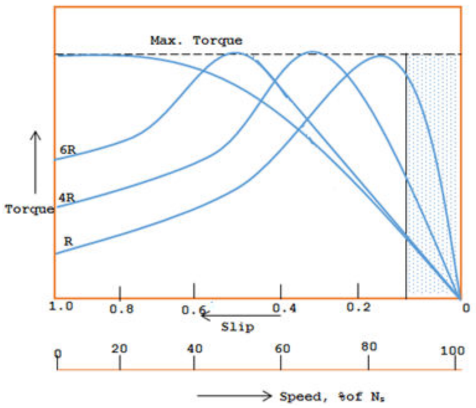
$$T = K\frac{s^2X_2}{(sX_2)^2 + (sX_2)^2} \quad \text{where } K = \frac{3E_2^2}{2\pi n_s}$$

$$T = K\frac{s^2X_2}{2(sX_2)^2} = \frac{K}{2X_2} \qquad T_{max} = \frac{3}{2\pi n_s}\frac{E_2^2}{2X_2}$$

Thus, the magnitude of the maximum torque is same at both standstill and running conditions

TORQUE - SLIP CHARACTERISTICS

- The torque-slip characteristics in an induction motor shows the variation of the torque developed with respect to changes of slip.
- When the load on the motor is removed gradually the speed increases and the slip



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decreases

- Considering, the speed at standstill $N_r = 0$ the slip s =1 and as the speed increases from 0 to N_s the slip s decreases from 1 to zero, any how the induction motor never rotates at N_s so the slip never becomes 0
- Let the torque in an induction motor is

$$T = \left(\frac{3}{2\pi n_s}\right)\frac{sE_2^2R_2}{R_2^2 + (sX_2)^2} \quad T\alpha\frac{sR_2}{R_2^2 + (sX_2)^2}$$

- For the smaller values of slips i.e $0 < s < s_m$, $sX_2 << R_2$ so neglecting sX_2 , the torque in this smaller range of slips is

$$T\alpha\frac{sR_2}{R_2^2} \quad T\alpha\frac{s}{R_2} \quad T\alpha\, s$$

- As the torque is directly proportional to slip s, Therefore as slip increases the torque increases linearly and attains maximum torque when slip $s = s_m$
- For the larger values of slips i.e $s_m < s < 1$, R2 << sX_2 so neglecting R_2 , the torque in this larger range of slips is

$$T\alpha\frac{R_2}{s{X_2}^2} \quad T\alpha\frac{1}{s}$$

- As the torque is inversely proportional to slip s, Therefore as slip increases the torque decreases linearly and falls to the value of standstill torque T_{st} at s = 1

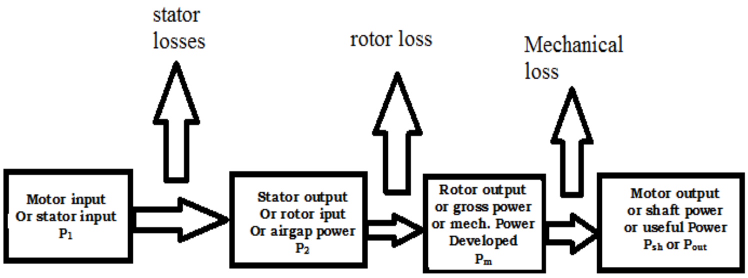
Salient points:

1. The maximum value of the torque is independent to the rotor resistance
2. The slip at which the maximum torque occurs (s_m) depends on the rotor resistance
3. The motor develops maximum torque at starting itself by making s_m =1 which is possible when $R_2 = X_2$

POWER STAGES IN A 3-PHASE INDUCTION MOTOR

In a 3-Phase induction motor the power losses occurs in stator and rotor

- Stator losses = Stator core loss + stator Cu loss
- Rotor losses = Rotor Cu loss
- Mechanical loss = Friction and windage loss



Therefore,

- Stator output power (P_2) = Stator input power (P_1) – stator losses
- Rotor output power (P_m) = Rotor input power (P_2) – rotor Cu loss
- Motor output power (P_{sh}) = Rotor output power (P_m) – Mechanical loss

Relationship between rotor input, rotor output and slip in a 3-Phase induction motor

The mechanical power in a motor is given by

$$P_m = \frac{2\pi N_r}{60}T \text{ or } P_2 = \frac{2\pi N_s}{60}T$$

Where P_m is the mechanical or gross output power and P2 is the air gap power or rotor input. T = torque in the motor

$$P_m = \omega_r T \text{ ---- (1)} \qquad \text{and} \qquad P_2 = \omega_s T \text{ ---- (2)}$$

Eq (2) – Eq (1) = P_2 - P_m = $\omega_s T - \omega_r T = (\omega_s - \omega_r)T$ ---- (3)

Divide Eq (3) with Eq (2)

$$\frac{P_2 - P_m}{P_2} = \frac{\text{Rotor Cu Loss}}{P_2} = \frac{(\omega_s - \omega_r)}{\omega_s} = s$$

Rotor cu loss (RCL) = sP_2 ----- (4)

Divide Eq (1) with Eq (2)

$$\frac{P_m}{P_2} = \frac{\omega_r}{\omega_s} = \frac{P_2 - RCL}{P_2} = \frac{P_2 - sP_2}{P_2} = \frac{P_2(1-s)}{P_2} = 1 - s$$

P_m = (1-s) P_2 ---- (5)

Divide Eq (5) with Eq (4)

$$\frac{P_m}{RCL} = \frac{P_2(1-s)}{sP_2} = \frac{(1-s)}{s}$$

$$P_m = \frac{(1-s)}{s} \times RCL \text{ ---- (6)}$$

Finally from Eq's (4), (5) & (6) ***P_2 : RCL:: P_m = 1 : s :: (1-s)***

Thus,

$$\eta = \frac{motor\ output}{motor\ input} = \frac{motor\ output}{motor\ output + mech\ loss + rotor\ cu\ loss + stator\ core\ loss + stator\ cu\ loss}$$

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STARTING METHOD FOR INDUCTION MOTORS

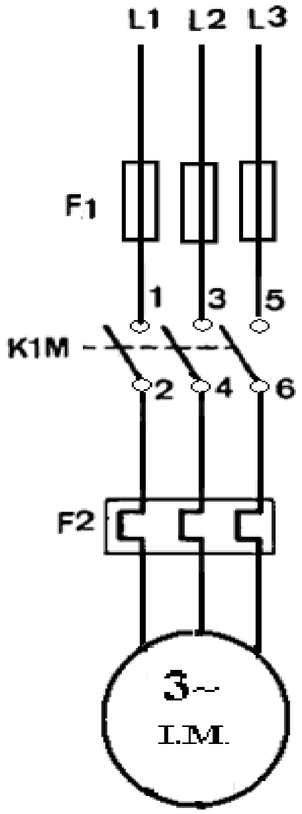
- A 3-phase induction motor is theoretically self starting. The stator of an induction motor consists of 3-phase windings, which when connected to a 3-phase supply creates a rotating magnetic field. This will link and cut the rotor conductors which in turn will induce a current in the rotor conductors and create a rotor magnetic field. The magnetic field created by the rotor will interact with the rotating magnetic field in the stator and produce rotation.
- Therefore, 3-phase induction motors employ a starting method not to provide a starting torque at the rotor, but because of the following reasons;

  1. Reduce heavy starting currents and prevent motor from overheating.
  2. Provide overload and no-voltage protection.

- There are many methods in use to start 3-phase induction motors. Some of the common methods are;

  - Direct On-Line Starter (DOL)
  - Star-Delta Starter
  - Auto Transformer Starter
  - Rotor resistance Starter

Direct On-Line Starter (DOL)

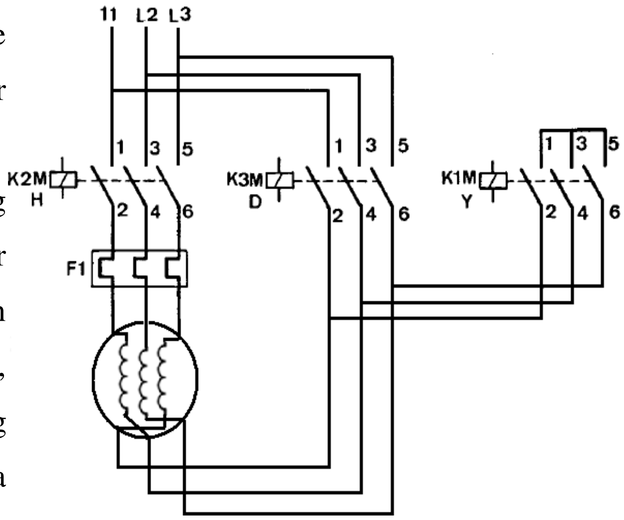


1. The Direct On-Line (DOL) starter is the simplest and the most inexpensive of all starting methods and is usually used for squirrel cage induction motors.
2. It directly connects the contacts of the motor to the full supply voltage. The starting current is very large, normally 6 to 8 times the rated current.
3. The starting torque is likely to be 0.75 to 2 times the full load torque.
4. In order to avoid excessive voltage drops in the supply line due to high starting currents, the DOL starter is used only for motors with a rating of less than 5KW
5. There are safety mechanisms inside the DOL starter which provides protection to the motor as well as the operator of the motor.
6. The DOL starter consists of a coil operated contactor K1M controlled by start and stop push buttons.

7. On pressing the start push button S1, the contactor coil K1M is energized from line L1. The three mains contacts (1-2), (3-4), and (5-6) in fig. are closed. The motor is thus connected to the supply.
8. When the stop push button S2 is pressed, the supply through the contactor K1M is disconnected. Since the K1M is de-energized, the main contacts (1- 2), (3-4), and (5-6) are opened. The supply to motor is disconnected and the motor stops.

Star-Delta Starter

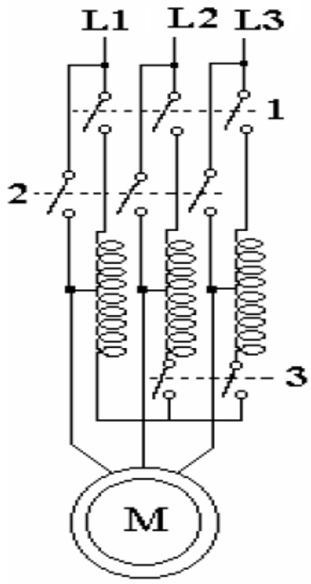
1. The star delta starting is a very common type of starter and extensively used, compared to the other types of the starters. This method used reduced supply voltage in starting. Figure shows the connection of a 3phase induction motor with a star – delta starter.



2. The method achieved low starting current by first connecting the stator winding in star configuration, and then after the motor reaches a certain speed, throw switch changes the winding arrangements from star to delta configuration.
3. By connecting the stator windings, first in star and then in delta, the line current drawn by the motor at starting is reduced to one-third as compared to starting current with the windings connected in delta.
4. At the time of starting when the stator windings are start connected, each stator phase gets voltage $\frac{V_L}{\sqrt{3}}$ where V_L is the line voltage.
5. Since the torque developed by an induction motor is proportional to the square of the applied voltage, star- delta starting reduced the starting torque to one – third that obtainable by direct delta starting.

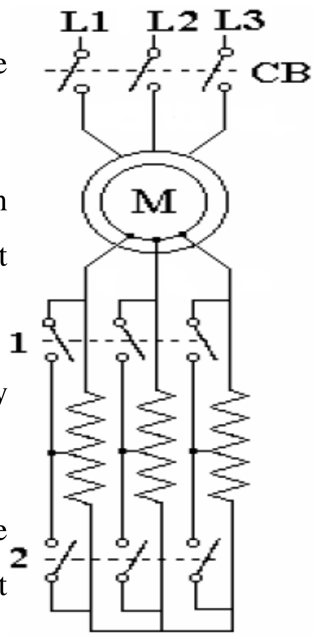
   a. K2M Main Contactor
   b. K3M Delta Contactor
   c. K1M Star Contactor
   d. F1 Thermal Overload Relay

Auto Transformer Starter



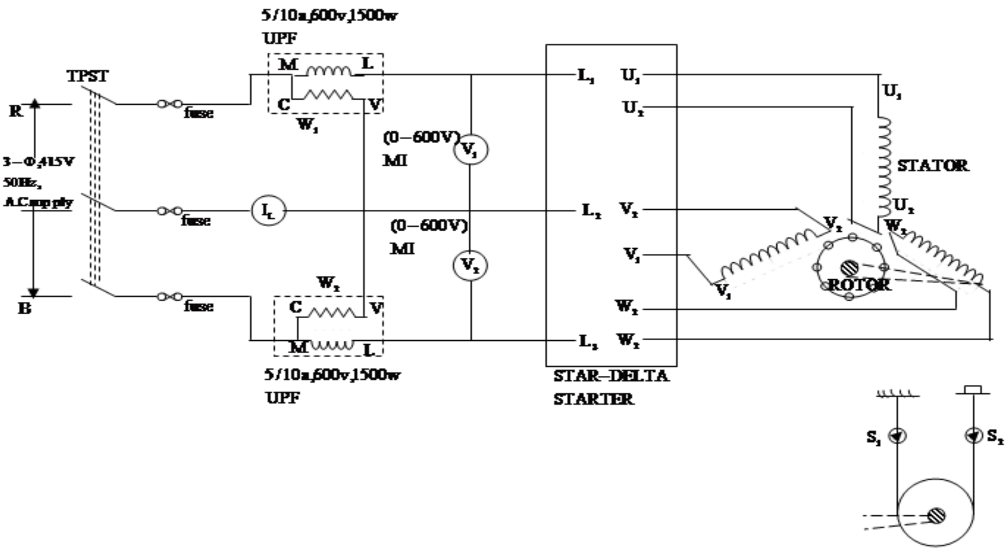
1. The operation principle of auto transformer method is similar to the star delta starter method.
2. The starting current is limited by (using a three phase auto transformer) reduce the initial stator applied voltage.
3. The auto transformer starter is more expensive, more complicated in operation and bulkier in construction when compared with the star – delta starter method.
4. But an auto transformer starter is suitable for both star and delta connected motors, and the starting current and torque can be adjusted to a desired value by taking the correct tapping from the auto transformer.
5. When the star delta method is considered, voltage can be adjusted only by factor of $\frac{1}{\sqrt{3}}$.

Rotor Resistance Starter



1. This method allows external resistance to be connected to the rotor through slip rings and brushes.
2. Initially, the rotor resistance is set to maximum and is then gradually decreased as the motor speed increases, until it becomes zero.
3. The rotor impedance starting mechanism is usually very bulky and expensive when compared with other methods.
4. It also has very high maintenance costs. Also, a considerable amount of heat is generated through the resistors when current runs through them.

BRAKE TEST ON 3-PHASE INDUCTION MOTOR.



1. The brake test is a direct method of testing. It consists of applying a brake to a water – cooled pulley mounted on the shaft of the motor.
2. A rope is wound round the pulley and its two ends are attached to two spring balances S_1 and S_2.
3. The tension of the rope can be adjusted with the help of swivels. Then, the force acting tangentially on the pulley = $(S_1 – S_2)$ Kgs.
4. If *r* is the pulley radius, the torque at the pulley, $T_{sh} = (S_1 – S_2)\, r$ kg m.
5. If "ω" is the angular velocity of the motor. $\omega = 2\pi N/60$, Where N is the speed in rpm.
6. Motor output $P_{out} = 9.81 \times 2\pi N (s_1 – s_2)\, r$ watts.
7. The motor input can be measured directly from the wattmeter's by summing w_1 and w_2 readings
8. Thus, the efficiency is calculated by taking the ratio of the motor output to the motor input.

Unit – 5 (BEE) R19&R20 Regulations – I ECE II Semester

Special Machines: Principle of operation and construction - single phase induction motor - shaded pole motors – capacitor motors and AC servomotor.

SINGLE PHASE MOTORS

- As the name suggests, these motors are used on single – phase supply. Single phase motors are the most common type of electric motors, which finds wide domestic, commercial and industrial applications.
- Single phase motors are small size motors of fraction – kilowatt ratings. Domestic applications like fans, hair driers, washing machines, mixers, refrigerators, food processors and other kitchen equipment employ these motors.
- These motors also find applications in air – conditioning fans, blower's office machinery etc.

Single phase motors may be classified into the following basic types:

1. Single phase induction motors
2. AC. Series motor (universal motor)
3. Repulsion motors
4. Synchronous motor

Single Phase Induction Motor

- A single phase induction motor is very similar to 3 – phase squirrel cage induction motor. It has a squirrel – cage rotor identical to a 3 - phase squirrel cage motor and a single – phase winding on the stator. Unlike 3 – phase induction motor, a single phase induction motor is not self starting but requires some starting means.
- Figure (1) shows 1 – phase induction motor having squirrel cage rotor and single phase distributed stator winding.

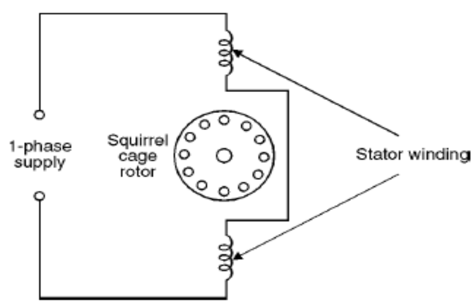


Fig. (1) Single – phase induction motor

1

- If the stator winding is connected to single – phase a.c. supply, the stator winding produces a magnetic field that pulsates in strength in a sinusoidal manner.
- The field polarity reverses after each half cycle but the field does not rotate. Consequently, the alternating flux cannot produce rotation in a stationary squirrel cage rotor.
- However, if the rotor is started by auxiliary means, the motor will quickly attain the final speed. The behavior of single – phase induction motor can be explained on the basic of double – field revolving theory.

Double – Field Revolving Theory

- The pulsating field produced in single phase AC motor is resolved into two components of half the magnitude and rotating in opposite directions at the same synchronous speed.
- Let Φ_m be the pulsating field which has two components each of magnitude $\Phi_m/2$ Both are rotating at the same angular speed ω rad/sec but in opposite direction as shown in the Figure (2-a).
- The resultant of the two fields is $\Phi_m \cos\theta$. Thus the resultant field varies according to cosine of the angle θ. The wave shape of the resultant field is shown in Figure (2-b).

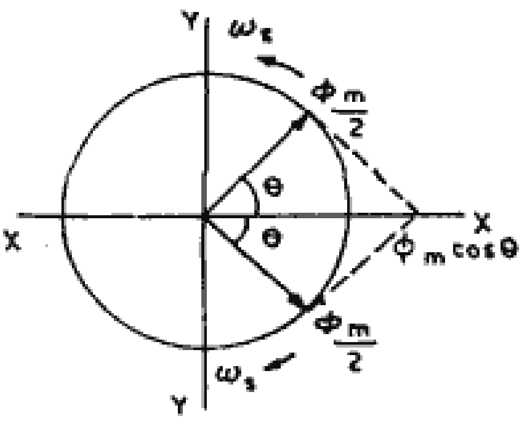


Fig. (2-a)

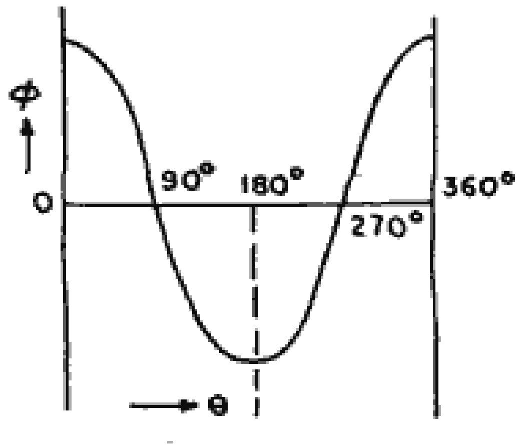


Fig. (2-b)

- Thus the alternating flux produced by stator winding can be presented as the sum of two rotating fluxes Φ_1 and Φ_2 each equal to one half of the maximum value of alternating flux and each rotating at synchronous speed in opposite directions.
- Let the flux Φ_1 (forward) rotate in anticlockwise direction and flux Φ_2 (backward) in clockwise direction. The flux Φ_1 will result in the production of torque T_1 in the anticlockwise direction and flux Φ_2 will result in the production of torque T_2 in the clockwise direction.

- At standstill, these two torques are equal and opposite and the net torque developed is zero. Therefore, single – phase induction motor is not self – starting. This fact is illustrated in fig. (3)

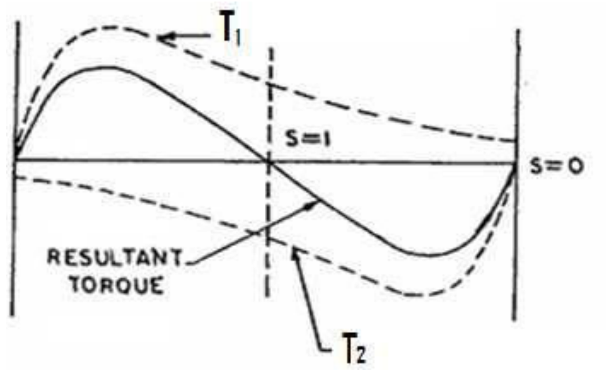


Fig. (3) Torque – slip characteristic of 1- phase induction motor

Rotor Running

- Assume that the rotor is started by spinning the rotor or by using auxiliary circuit, in say clockwise direction.
- The flux rotating in the clockwise direction is the forward rotating flux Φ_f and that in the other direction is the backward rotating flux Φ_b.
- The slip with respect to the forward flux will be $s_f = \frac{N_s - N}{N_s}$

Where

N_s = synchronous speed

N = speed of rotor in the direction of forward flux

- The rotor rotates opposite to the rotation of the backward flux. Therefore, the slip w.r.t the backward flux will be

$$s_b = \frac{N_s - (-N)}{N_s} = \frac{N_s + N}{N_s} = \frac{2N_s - N_s + N}{N_s} = \frac{2N_s}{N_s} - \frac{(N_s - N)}{N_s} = 2 - s$$

- Thus for forward rotating flux, slip is *s* (less than unity) and for backward rotating flux, the slip is 2-s (greater than unity) since for usual rotor resistance/reactance ratios, the torque at slips of less than unity are greater than those at slips of more than unity, the resultant torque will be in the direction of the rotation of the forward flux.
- Thus if the motor is once started, it will develop net torque in the direction in which it has been started and will function as a motor.

Starting of Single Phase Induction Motors

The single phases induction motors are classified based on the method of starting method and in fact are known by the same name descriptive of the method.

1. **Split – phase Induction Motor**

- The stator of a split – phase induction motor has two windings,
    1. Main winding
    2. Auxiliary winding.

These windings are displaced in space by 90 electric degrees as shown in figure (4-a).

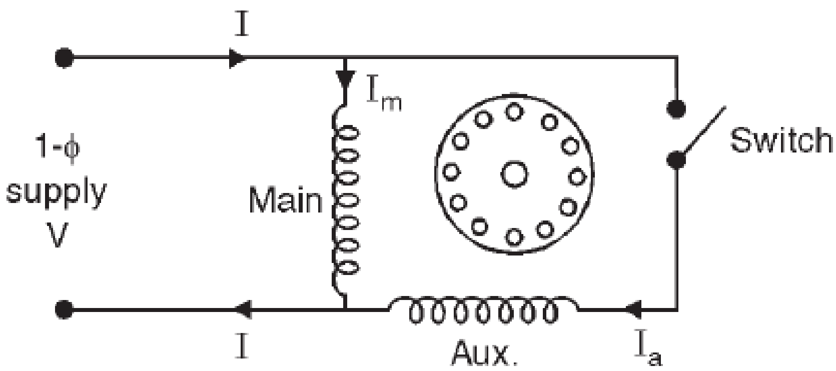


Fig.(4-a) split phase I.M.

- The auxiliary winding is made of thin wire so that it has a high R/X ratio as compared to the main winding which has thick super enamel copper wire.
- When the two stator windings are energized from a single – phase supply, the current I_m and I_a in the main winding and auxiliary winding lag behind the supply voltage V, and I_a leading the current I_m as shown in figure (4-b).

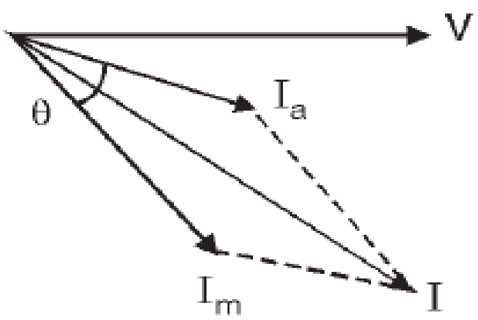
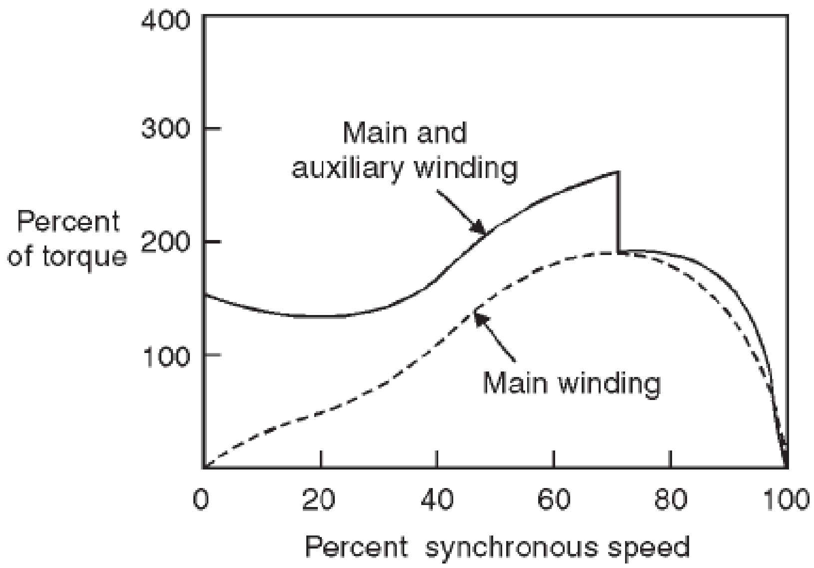


Fig.(4-b) Phasor diagram at starting

- This means the current through auxiliary winding reaches maximum value first and the mmf or flux due to I_a lies along the axis of the auxiliary winding and after some time the current I_m reaches maximum value and the mmf due to I_m lies along the main winding axis.
- Thus the motor becomes a 2 – phase unbalanced motor. Because of these two fields a starting torque is developed and the motor becomes a self starting motor.
- After the motor starts, the auxiliary winding is disconnected usually by means of centrifugal switch that operates at about 75% of synchronous speed. Finally the motor runs because of the main winding.
- Since this being single phase some level of humming noise is always associated with the motor during running. The power rating of such motors generally lies between 60- 250W. The typical torque – speed characteristic is shown in fig (4-c).



Characteristics

- Due to their low cost, split – phase induction motors are most popular single – phase motors in the market
- Since the starting winding is made of thin wire, the current density is high and the winding heats up quickly. If the starting period exceeds 5 seconds, the winding may burn out unless the motor is protected by built – in thermal relay. This motor is, therefore, suitable where starting periods are not frequent.

2. Capacitor – Start Motor

- Capacitors are used to improve the starting and running performance of the single phase inductions motors.
- The capacitor – start motor is identical to a split – phase motor except that the starting winding has as many turns as the main winding.
- Moreover, a capacitor C is connected in series with the starting winding as shown in fig (5-a).

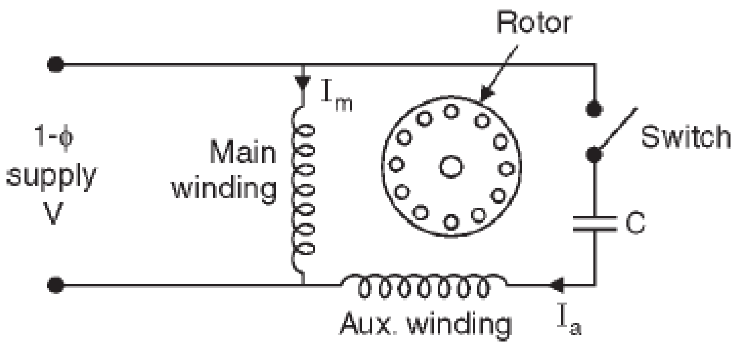
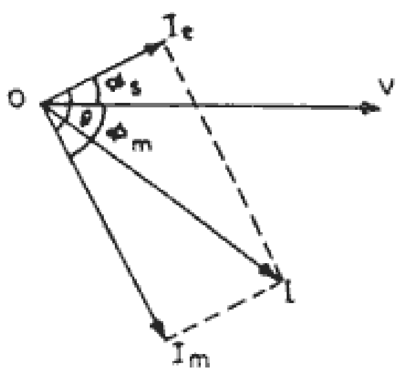


Fig.(5-a) Capacitor Start Motor

- The value of capacitor is so chosen that I_a leads I_m by about 90^o (Fig.5-b) so that the starting torque is maximum for certain values of I_a and I_m.
- Again, the starting winding is opened by the centrifugal switch when the motor attains about 75% of synchronous speed.
- The motor then operates as a single – phase induction motor and continues to accelerate till it reaches the normal speed.



The typical torque – speed characteristic is shown in fig (5-c).

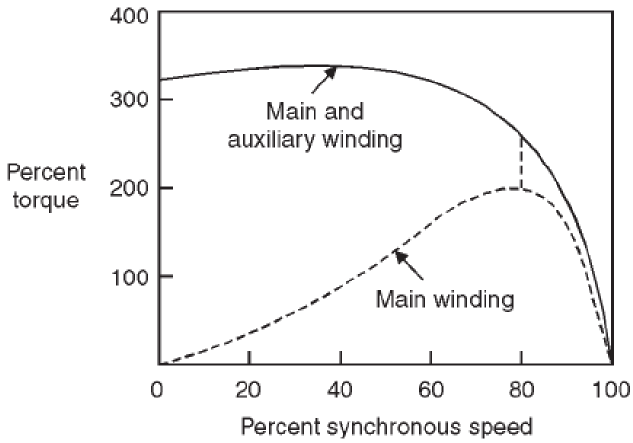


Fig. (5-c)

Characteristics

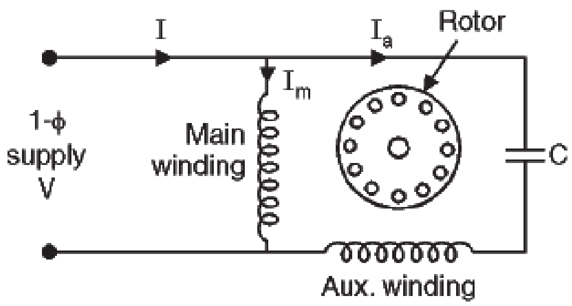
- Although starting characteristics of a capacitor – start motor are better than those of a split – phase motor, both machines possess the same running characteristics because the main windings are identical.
- The phase angle between the two currents is about 90 compared to about 25^o in a split – phase motor. Consequently, for the same starting torque, the current in the starting winding is only about half that in a split – phase motor.
- Therefore, the starting winding of a capacitor start motor heats up less quickly and is well suited to applications involving either frequent or prolonged starting periods.
- Capacitor – start motors are used where high starting torque is required and where high starting period may be long e.g. to drive:

a) Compressors b) large fans c) pumps d)high inertia loads

The power rating of such motors lies between 120W and 0.75 kW.

3. Permanent – Split Capacitor Motor

- In this motor, as shown in fig.(6-a), the capacitor that is connected in series with the auxiliary winding is not cut out after starting and is left in the circuit all the time.
- This simplifies the construction and decreases the cost because the centrifugal switch is not needed.
- The power factor, torque pulsation, and efficiency are also improved because the motor runs as a two – phase motor. The motor will run more quietly.
- The capacitor value is of the order of 20 – 50F and because it operates continuously, it is an ac paper oil type.
- The capacitor is compromise between the best starting and running value and therefore starting torque is sacrificed. The typical torque – speed characteristic is shown in fig (6-b).



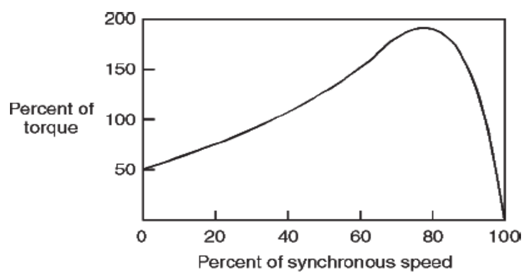


Fig.(6-a) Permanent – Split Capacitor Motor

Fig.(6-b) torque – speed characteristic

Characteristic

- These motor are used where the required starting torque is low such as air – moving equipment i.e. fans, blowers and voltage regulators and also oil burners where quite operation is particularly desirable.

4. Capacitor - Start Capacitor - Run

Two capacitor, one for starting and one for running, can be used, as shown in fig.(7-a).

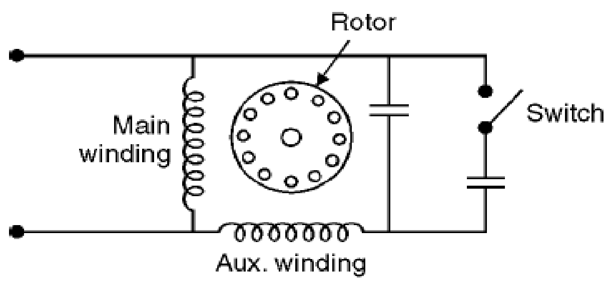


Fig. (7-a) Capacitor - Start Capacitor – Run motor

Theoretically, optimum starting and running performance can be achieved by having two capacitors. The starting capacitor is larger in value and is of the ac electrolytic type. The running capacitor permanently connected in series with the starting winding, is of smaller value and is of the paper oil type. Typical values of these capacitors for a 0.5 hp are C_s =300µF, C_r =40µF. The typical torque – speed characteristic is shown in fig. (7- b).

Characteristic

- Ability to start heavy loads
- Extremely quiet operation
- Higher efficiency and power factor

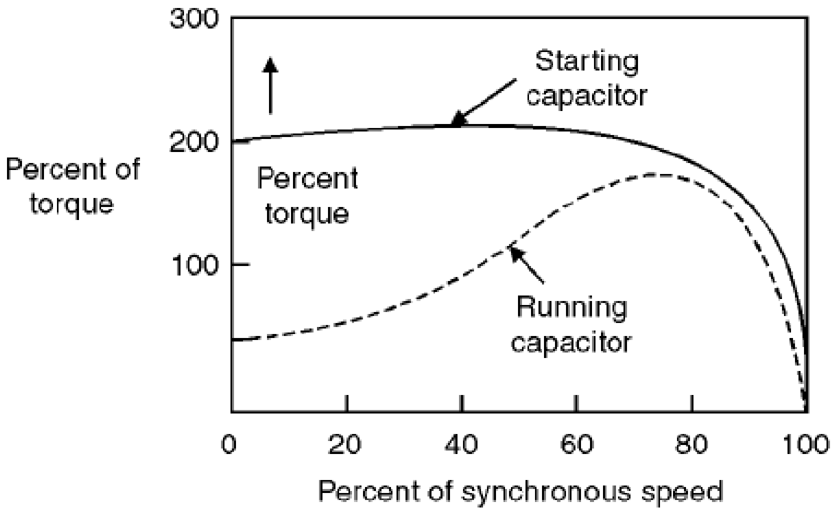


Fig.(7-b) torque – speed characteristic

- Ability to develop 25 per cent overload capacity. Hence, such motors are ideally suited where load requirements are severe as in the case of compressors and conveyors etc.

5. **Shaded Pole Induction Motor**

- These motors have a salient pole construction. A shaded band consisting of a short – circuited copper turn, known as a shading coil, is used on one portion of each pole, as shown in fig(8-a).
- When alternating current flow in the field winding, an alternating flux is produced in the field core. A portion of this flux links with the shading coil, which behaves as short – circuited secondary of a transformer.
- A voltage is induced in the shading coil, and this voltage circulates a current in it. The induced

current produces a flux called the induced flux which opposes the main core flux.

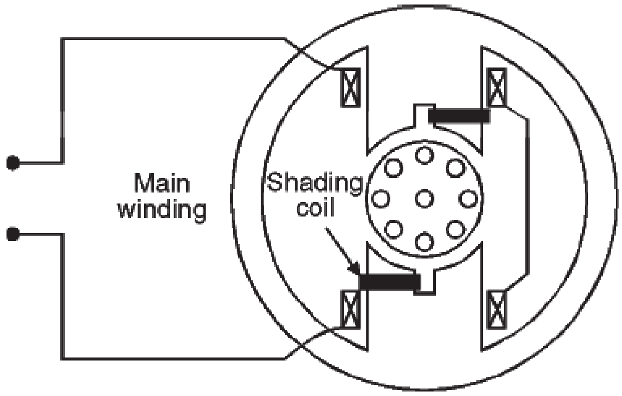


Fig (8-a) Shaded Pole Induction Motor

- The shading coil, thus, causes the flux in the shaded portion to lag behind the flux in the unshaded portion of the pole.
- At the same time, the main flux and the shaded pole flux are displaced in space. This displacement is less than 90^o. Since there is time and space displacement between the two fluxes, the conditions for setting up a rotating magnetic field are produced.
- Under the action of the rotating flux a starting torque is developed on the cage rotor. The direction of this rotating field (flux) is from the unshaded to the shaded portion of the pole.

The typical torque-speed characteristic is shown in fig. (8-b).

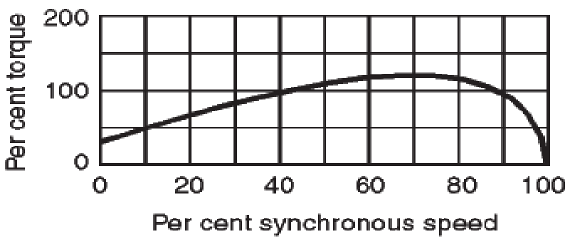


Fig.(8-b) torque – speed characteristic

Characteristic

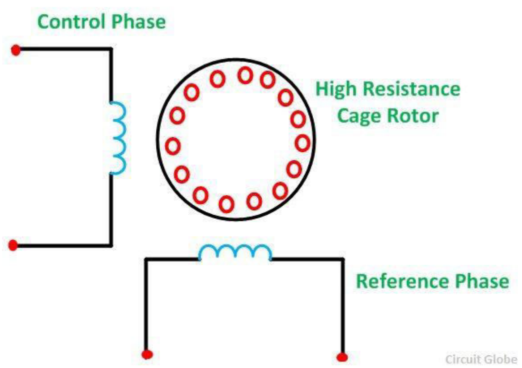
- The salient features of this motor are extremely simple construction and absence of centrifugal switch
- Since starting torque, efficiency and power factor are very low, these motors are only suitable for low power applications e.g. to drive: Small fans b) toys c) hair driers. The power rating of such motors is up to about 30 W.

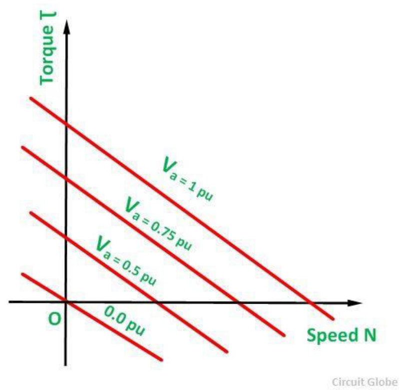
AC SERVO MOTOR

Most of the ac servo motors are of the two – phase squirrel cage induction type and are used for low power applications. However recently three phase induction motors have been modified for high power servo systems which had so far been using high power dc servo motors.

Two – Phase AC Servo motor

- Such motors normally run on a frequency of 60Hz or 400Hz (for airborne systems). The stator has two distributed windings which are displaced from each other by 90^0 (electrical).
- The main winding (also called the reference or fixed phase) is supplied from a constant voltage source $V_m \angle 0^0$.
- The other winding (also called the control phase) is supplied with a variable voltage of the same frequency as the reference phase but is phase – displaced by 90^0 (electrical).
- The control phase voltage is controlled by an electronic controller. The speed and torque of the rotor are controlled by the phase difference between the main and control windings.
- Reversing the phase difference from leading to lagging reverses the motor direction
- Since the rotor bars have high resistance, the torque – speed characteristic for various armature voltages are almost linear over a wide speed range particularly near the zero speed.
- The motor operation can be controlled by varying the voltage of the main phase while keeping that of eh reference phase constant.





UNIT WISE IMPORTANT QUESTIONS

Unit 1:-

1. Explain the principle of operation of dc generator?

2. Derive emf equation of dc generator?

3. Derive torque equation of dc motor?

4.what are different types of dc machines?

5. Explain briefly about three point starter?

6. Explain various losses in a dc generator?

Unit2:-

1.Explain the principle and operation of a transformer?

2.Explain the constructional details of a transformer?

3.Deduce an emf equation of a transformer?

4.Explain different losses in transformer?

5.Explain briefly about OC test of a transformer?

6.Explain the SC test of a transformer?

Unit 3:-

1.Explain the principle operation of alternators?

2.Explain the constructional details of alternators?

3.Explain the working principle of synchronous generator?

4.Explain briefly about construction of 3 phase synchronous motor?

5.what is the operating principle of synchronous motor?

6.Deduce emf equation of 3 phase alternator?

Code No: R201214 **R20** SET - 1

I B. Tech I Semester Regular Examinations, September- 2021

BASIC ELECTRICAL ENGINEERING

(Com. to ECE, EIE, ECT)

Time: 3 hours Max. Marks: 70

Answer any five Questions one Question from Each Unit
All Questions Carry Equal Marks

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UNIT-I

1 a) Distinguish between (7M)
(i) Cumulatively wound and differentially wound dc machines.
(ii) Long shunt and short shunt dc machines.

b) A 4-pole generator with 400 armature conductors has a useful flux of 0.04 Wb per pole. What is the emf produced if the machine is wave wound and runs at 1200 rpm? What must be the speed at which the machine should be driven to generate the same emf if the machine is lap wound? (7M)

Or

2 a) What is meant by back emf? Explain the principle of torque production in a dc motor. (7M)

b) An 8-pole, 400 V shunt motor has 960 wave connected armature conductors. The Full load armature current is 40 A and the flux per pole is 0.02 Wb. The armature Resistance is 0.1 W and the contact drop is 1 V per brush. Calculate the full load speed of the motor. (7M)

UNIT-II

3 a) Draw and explain the equivalent circuit of a Single-phase transformer. (7M)

b) A single-phase transformer has 400 primary and 1000 secondary turns. The net cross-sectional area of the core is 60 cm^2. The primary winding is connected to a 500 V supply. Find the (i) peak value of the core flux density and the (ii) emf induced in the secondary winding. (7M)

Or

4 The efficiency of a 10 kVA, 2000/400 V single phase transformer at unity power factor is97% at rated load and also at half rated load. Determine the transformer core losses and copper losses. (14M)

UNIT-III

5 a) Distinguish in detail between Salient pole type and Non – salient type of rotor in synchronous machine. (7M)

b) A 2500 V, three-phase star connected synchronous motor has a resistance of 0.35 W per phase and synchronous reactance of 2.2 Ω per phase. The motor is operating at0.75 power factor leading with a line current of 250 A. Determine the excitation voltage per phase. (7M)

Or

6 a) Derive the expression for induced emf in a synchronous machine. (7M)

b) Distinguish in detail between the synchronous motor and Three phase induction motor. (7M)
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UNIT-IV

7	a)	Explain the concept behind the production of rotating field in a three-phase induction motor.	(7M)
	b)	The frequency of the emf in the stator of a 4-pole induction motor is 50 Hz, and that in the rotor is 2 Hz. What is the slip and at what speed is the motor running?	(7M)

Or

8	a)	List the various losses that occur in a three-phase induction motor and explain each one of i.	(7M)
	b)	Explain the need for conducting the brake test on a Three phase induction motor and how it is done.	(7M)

UNIT-V

9	a)	Distinguish in detail between Single – phase induction motors and Three phase induction motors.	(7M)
	b)	Explain the construction and working principle of shaded pole motor with neat diagrams.	(7M)

Or

10	a)	Discuss the various methods for starting single phase induction motors.	(7M)
	b)	Explain the construction and working principle of AC servo motor with neat diagrams.	(7M)