2018-19 Onwards (MR-18)	MALLA REDDY ENGINEERING COLLEGE (Autonomous)	B.Tech. V Semester		
Code: 80213	AC MACHINES	L	T	P
Credits: 4		3	1	-

Prerequisites: Electromagnetic Fields

Course Objectives:
This course facilitates to study the performance of induction motors which is main drive for industrial applications. It also emphasis about the performance analysis of synchronous machines.

MODULE- I: Three Phase Induction Motors 13 Periods

Three phase induction motors - Construction details - Production of a rotating magnetic field - Principle of operation - Rotor EMF and rotor frequency - Rotor reactance, rotor current and power factor - Equivalent circuit - Phasor diagram - Crawling and cogging - Power stages.

MODULE-II: Performance of Induction Motors 13 Periods

Rotor power input, Rotor copper loss and mechanical power developed and their inter relation - Torque equation - Expressions for maximum torque and starting torque – Torque slip characteristics - Condition for maximum torque – Relation between torque and slip – Losses and efficiency – No load and blocked rotor test – Equivalent circuit – Circle diagram – Induction generator.

MODULE-III: Single Phase Induction Motors 12 Periods

A: Single phase induction motors – Principle of operation - Double revolving field theory - Split phase induction motor - Capacitor start induction motor - Capacitor start and run induction motor.

B: Equivalent circuit - Shaded pole induction motor.

MODULE IV Synchronous Generators 13 Periods

Synchronous generator – Construction, working principle - EMF equation – Armature reaction – Regulation methods – EMF, MMF,ZPF methods – Synchronizing to infinite bus bars – Two reaction theory – Parallel operation of synchronous generators.

MODULE V Synchronous Motors 13 Periods

Synchronous motor – Constructional features, principle of operation of synchronous motor – Methods of starting – Power developed by a synchronous motor – Synchronous motor with different excitations – Effect of increased load with constant excitation, effect of changing excitation constant load – Torque equation – V curve and inverted V curve – Hunting.

Text Books

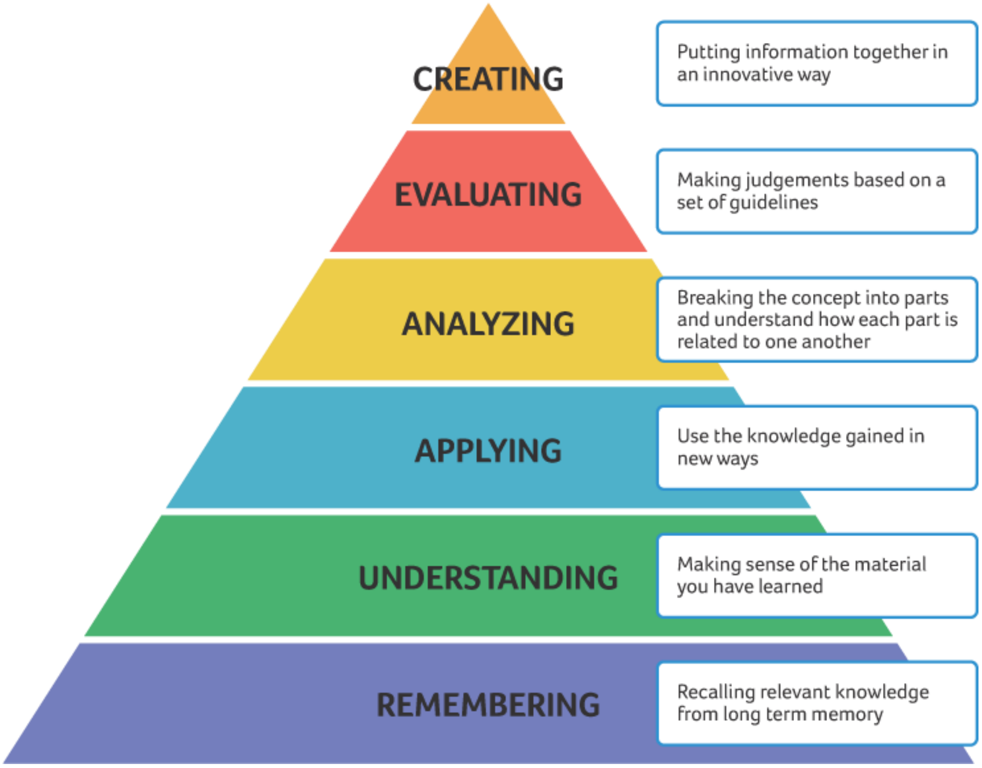
1. P.S. Bimbra, **"Electrical Machinery"**, Khanna Publishers, New Delhi, 7th Edition, 2011.
2. J.B.Gupta, **"Theory & Performance of Electrical Machines"**, S.K. Kataria & Sons, 15th Edition, 2015

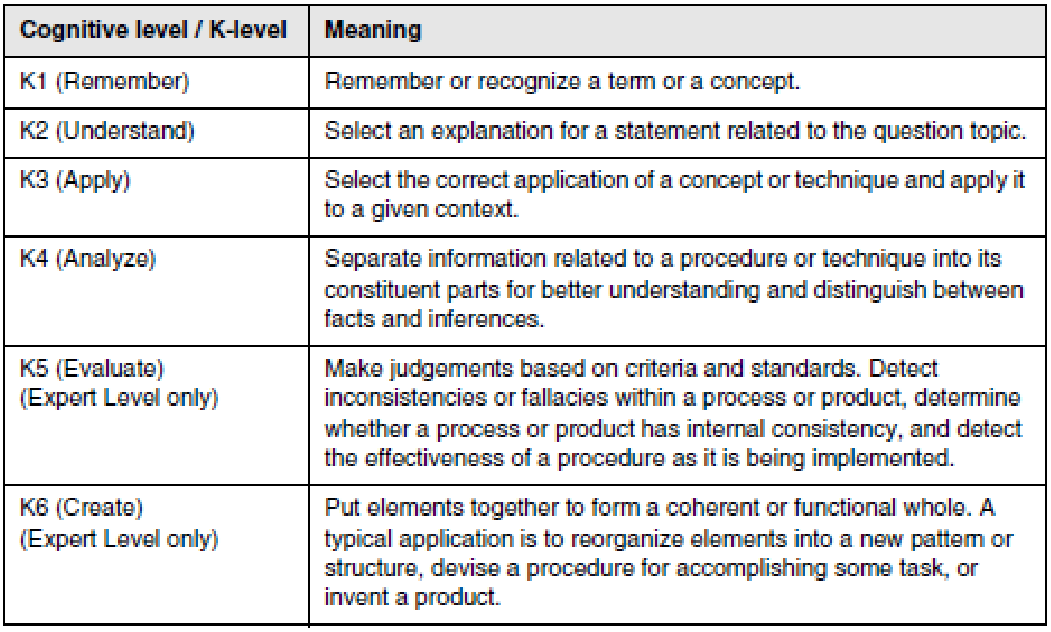
References

1. M.G Say, **“Performance and Design of A.C Machines”**, 3rd Edition, BPB Publishers, 2002.
2. A.E.Fitzgerald, C.Kingsley and S.Umans, **“Electric Machinery”**, Tata McGraw-Hill Companies, 7th Edition, 2013.
3. I.J.Nagrath & D.P.Kothari, **“Electric Machines”**, Tata McGraw Hill, 4th Edition, 2010.
4. S. Kamakashaiah, **“Electromechanics-II (Transformers and Induction Motors)”**, Hitech Publishers.
5. R.K.Rajput, **“Electrical Machines”**, Laxmi Publications Pvt., Ltd., New Delhi, 4th Edition, 2006.

Bloom’s Revised Taxonomy

There are six levels of cognitive learning according to the revised version of Bloom’s Taxonomy. Each level is conceptually different. The six levels are remembering, understanding, applying, analyzing, evaluating, and creating.





Cognitive level / K-level	Meaning
K1 (Remember)	Remember or recognize a term or a concept.
K2 (Understand)	Select an explanation for a statement related to the question topic.
K3 (Apply)	Select the correct application of a concept or technique and apply it to a given context.
K4 (Analyze)	Separate information related to a procedure or technique into its constituent parts for better understanding and distinguish between facts and inferences.
K5 (Evaluate) (Expert Level only)	Make judgements based on criteria and standards. Detect inconsistencies or fallacies within a process or product, determine whether a process or product has internal consistency, and detect the effectiveness of a procedure as it is being implemented.
K6 (Create) (Expert Level only)	Put elements together to form a coherent or functional whole. A typical application is to reorganize elements into a new pattern or structure, devise a procedure for accomplishing some task, or invent a product.

MALLA REDDY ENGINEERING COLLEGE (AUTONOMOUS)

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

VISION & MISSION

(This document is to be presented to the students during the first week of commencement of classes and a soft copy to every student of the class by the course coordinator)

VISION OF THE INSTITUTE

To be a premier center of professional education and research, offering quality programs in a socio-economic and ethical ambience.

MISSION OF THE INSTITUTE

- *To impart knowledge of advanced technologies using state-of-the-art infrastructural facilities.*
- *To inculcate innovation and best practices in education, training and research.*
- *To meet changing socio-economic needs in an ethical ambiance.*

VISION OF THE DEPARTMENT

To foster quality education, training and research in the field of Electrical and Electronics Engineering and ethically committed engineers to meet the technological needs of the society.

MISSION OF THE DEPARTMENT

- *To impart knowledge of advanced technologies for continual improvement in teaching, learning and research.*
- *To Provide well-balanced curriculum and industry collaborations.*
- *To Inculcate social values and leadership qualities*

MALLA REDDY ENGINEERING COLLEGE (AUTONOMOUS)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
COURSE DELIVERY PLAN

(This document is to be presented to the students during the first week of commencement of classes and a soft copy to every student of the class by the course coordinator)

1	**Programme /Branch** (or Specialization)	:	B.Tech , EEE
2	**Class**	:	III Year , I Semester
3	**Course Code**	:	80213
4	**Course Title**	:	AC MACHINES
5	**Course Type & Hours**	:	Theory , 60 Hrs.
6	**Course Category & Credits**	:	Professional Common Course & 4 Credits
7	**Academic Year**	:	2020-21
8	**Regulation**	:	MR18
9	**Staff In charge**	:	**P.GANESH, Assistant Professor , Department of EEE,** E-mail: ganeshp5891@gmail.com
11	**Prerequisites**	:	Electromagnetic Fields

12 **Course Overview**

Modern power transmission is utilizing voltages between 345 kV and 1150 kV, A.C. Distances of transmission line, bulk powers handled, power loss minimization and economic considerations have increased to such an extent that extra high voltages and ultra-high voltages (EHV and UHV) are necessary. The problems encountered with such high voltage transmission lines exposed are electrostatic fields near the lines, audible noise, radio interference, corona losses, carrier and TV interference, high voltage gradients, heavy bundled conductors, control of voltages at power frequency using shunt reactors, switched capacitors, overvoltage's caused by lightning and switching operations, long air gaps with weak insulating properties for switching surges, ground-return effects, and many more.

This course covers all topics that are considered essential for understanding the operation and design of EHV ac overhead lines. Theoretical analyses of all problems combined with practical application are dealt in this course

13 **Course Objective**

This course facilitates to study the performance of induction motors which is main drive for industrial applications. It also emphasis about the performance analysis of synchronous machines.

14 **Text Book**

T1. R. D. Begamudre ,―EHVAC Transmission Engineering‖, New Age International (p) Ltd. 3rd Edition.
T2. K.R. Padiyar, ―HVDC Power Transmission Systems‖ New Age International (p) Ltd.2nd revised Edition, 2012.

15 **Reference Book**

R1. S. Rao ―EHVAC and HVDC Transmission Engg. Practice‖ Khanna publishers.
R2. Arrillaga.J ― High Voltage Direct Current Transmission‖ 2nd Edition (London) peter Peregrines, IEE, 1998.
R3. Padiyar.K.R, ― FACTS Controllers in Power Transmission and Distribution‖ New Age Int. Publishers, 2007.
R4. Hingorani H G and Gyugyi. L ― Understanding FACTS-Concepts and Technology of Flexible AC Transmission Systems‖ New York, IEEE Press, 2000.

16 **E-Learning Resources**

a) https://www.brainkart.com/article/EHVAC-and-HVDC-Transmission-System_12351/
b) http://alignment.hep.brandeis.edu/Lab/XLine/XLine.html
c) https://www.electronics-tutorials.ws/accircuits/reactive-power.html
d) https://www.thierry-corp.com/plasma/knowledge/corona-discharges/
e) https://electricalnotes.wordpress.com/2011/03/23/what-is-corona-effect/
f) https://electricalnotes.wordpress.com/2012/02/17/effects-of-high-voltage-transmission-lines-on-humans-and-plants/

17 **Course Outcomes**

At the end of the course, students will be able to

1. **Evaluate:** ***Determine*** the resistance, reactive ground parameters and power loss of the line with reference to EHVAC transmission.
2. **Evaluate:** Given the specifications of conductor and electrostatic fields, ***determine*** the voltage gradients for single and multi-conductor arrangements.
3. **Apply:** ***Calculate*** the Corona power loss, Audible Noise and Radio Interference levels for single phase and three phase EHV lines.
4. **Analyze:** ***Calculate*** the electrostatic field of double circuit EHV AC lines and analyze the effect of high electrostatic fields on humans, plants, animals and ***Analyze*** the travelling wave expressions and solutions.
5. **Analyze:** **Analyze** the different reactive power compensation schemes like static VAR compensator, synchronous condensers, shunt and series compensators to control the voltage of EHVAC transmission system.

18 **Program Outcome**

PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO 2	**Problem analysis**: Identify, formulate, review research literature and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

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

19 Programme Specific Outcomes (PSOs)

PSO1	Apply fundamental knowledge to identify, formulate, design and investigate various problems of electrical and electronic circuits, power electronics, power systems and renewable energy systems for specific requirements.
PSO2	Demonstrate proficiency in use of modern software tools & hardware to engage in life-long learning and to successfully adapt in multi-disciplinary environments.
PSO3	Solve ethically and professionally various Electrical Engineering problems in societal and environmental context and communicate effectively.

20. CO-PO Mapping

(3/2/1 indicates strength of correlation)

COs	Program Outcomes (Pos)												PSOs		
	1 K3	2 K6	3 K6	4 K4	5 K6	6 K3	7 K2	8 K3	9 K2	10 K2	11 K2	12 K3	1 K3	2 K2	3 K3
1 K5	1	2	-	-	-	-	-	-	-	-	-	-	2	-	-
2 K5	1	2	-	-	-	-	-	-	-	-	-	-	2	-	-
3 K3	1	3	-	-	1	1	1	-	-	-	-	-	1	1	1
4 K4	1	3	-	1	1	2	2	-	-	-	-	-	1	-	2
5 K4	1	3	-	1	-	1	-	-	-	-	-	1	1	-	-

3-Strong, 2-Medium, 1-Weak

21 . Course Outline

UNIT-I LINE AND GROUND REACTIVE PARAMETERS

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
1,2	Introduction & Necessity of EHV AC transmission, Advantages	CO1	K1	Lecture	T1,T2
3	Power handling capacity and Line losses	CO1	K3	Lecture	T1,T2
4,5	Mechanical considerations of transmission line	CO1	K2	Lecture	T1
6,7	Resistance of conductors, Properties of bundled conductors, Bundle spacing & Bundle radius	CO1	K3	Lecture	T1,R1
8	Problems	CO1	K5	Lecture	T1
9,10	Line inductance and capacitances	CO1	K3	Lecture	T1
11	Sequence inductances and capacitances	CO1	K3	Lecture	T1
12	Modes of propagation, Ground return	CO1	K4	Lecture	T1
13	Problem Solving	CO1	K5	Lecture	T1

UNIT-II : VOLTAGE GRADIENTS OF CONDUCTORS

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
14	Electrostatics Introduction	CO2	K2	Lecture	T1,T2
15	Field of sphere gap	CO2	K3	Lecture	T1
16	Field of line changes and properties	CO2	K3	Lecture	T1
17	Problem Solving	CO2	K5	Lecture	T1
18,19	Charge & potential relations for multi- conductors	CO2	K4	Lecture	T1
20	Surface voltage gradient on conductors	CO2	K4	Lecture	T1
21	Problem Solving	CO2	K5	Lecture	T1
22,23	Distribution of voltage gradient on sub-conductors of bundle	CO2	K3	Lecture	T1
24	Problem Solving	CO2	K5	Lecture	T1

UNIT – III : CORONA EFFECTS – I

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
25	Power loss and audible noise (AN)	CO3	K2	Lecture	T1
26	Corona loss formulae & charge voltage diagram	CO3	K2	Lecture	T1
27,28	Generation, characteristics, limits and measurements of AN	CO3	K2	Lecture	T1
29	Relation between 1-phase and 3-phase AN level.	CO3	K4	Lecture	T1
30	Problem Solving	CO3	K5	Lecture	T1
31	Radio interference (RI)	CO3	K2	Lecture	T1
32,33	Corona pulses generation, properties & limits	CO3	K2	Lecture	T1
34	Frequency spectrum & modes of propagation	CO3	K3	Lecture	T1
35,36	Excitation function & measurement of RI, RIV and excitation functions	CO3	K3	Lecture	T1
37	Problem Solving	CO3	K5	Lecture	T1

UNIT – IV: ELECTRO STATIC FIELD AND TRAVELING WAVE THEORY

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
38	Electrostatic field	CO4	K2	Lecture	T1
39	Calculation of electrostatic field of EHV/AC lines	CO4	K5	Lecture	T1
40	Effect on humans, animals and plants	CO4	K2	Lecture	T1,R2
41,42	Electrostatic induction in unenergized circuit of double-circuit line	CO4	K3	Lecture	T1
43	Electromagnetic interference	CO4	K2	Lecture	T1
44	Traveling wave expression and solution	CO4	K3	Lecture	T1
45	Source of excitation & terminal conditions	CO4	K2	Lecture	T1
46,47	Open circuited and short-circuited end Reflection and refraction coefficients	CO4	K3	Lecture	T1
47,48	Lumped parameters of distributed lines & generalized constants	CO4	K3	Lecture	T1
49	No load voltage conditions and charging current.	CO4	K4	Lecture	T1

UNIT – V : VOLTAGE CONTROL

Hour	Description of Portion to be Covered	Relevant CO Nos	Highest Cognitive Level	Delivery Method	Reference Materials
50	Long transmission line Model	CO5	K4	Lecture	
51	ABCD Constants	CO5	K5	Lecture	
52,53	Power circle diagram and its use	CO5	K3	Lecture	
54,55	Voltage control using synchronous condensers	CO5	K2	Lecture	R3,R4
56,57	Cascade connection of shunt and series compensation	CO5	K2	Lecture	R3,R4
58,59	Sub synchronous resonance in series capacitor & compensated lines	CO5	K2	Lecture	R3,R4
60,61	Static VAR compensating system	CO5	K2	Lecture	T2,R3,R4

Total No. of Hrs. Planned : 61

Total No. of Hrs. Taught :

22. Content Beyond Syllabus

a) Introduction to Grid Management (K1)
b) Protection against Over Voltages in HVAC Transmission System (K1)

23. Assignment

Assignment No. 1

a) Explain the effect of resistance of the conductor in EHVAC transmission system.
b) Explain in detail the inductance and capacitance of ground return and derive necessary expressions.
c) Explain field of sphere gap with their properties.
d) A point charge $Q = 10^{-6}$ coulomb (1 μC) is kept on the surface of a conducting sphere of radius r = 1 cm, which can be considered as a point charge located at the centre of the sphere. Evaluate the field strength and potential at a distance of 0.5 cm from the surface of the sphere. Also find the capacitance of the sphere, €r=1
e) Categorize the different expressions for corona loss based on voltage and voltage gradient.

Assignment No. 2

a) Explain in detail the different AN measuring meters with neat diagram.
b) (i) Obtain electrostatic fields of single circuit 3-phase EHV line.
(ii) Describe the difference between primary shock current and secondary shock current.
c) Discuss the effect of electrostatic field on (i) Human beings (ii) Animals (iii) Plant life, (iv) vehicles, (v) Fences
d) Explain in-detail about power circle diagram and its use.
e) Explain in-detail about voltage control using synchronous condensers

24. Evaluation

A) Continuous Internal Evaluation (CIE)

Attendance Evaluation

The allotment of 5 marks for attendance is as given below:

S.No.	% of Attendance Range	Marks
1	>90 and ≤ 100	5
2	>85 and ≤ 90	4
3	>80 and ≤ 85	3
4	>75 and ≤ 80	2

5	>70 and ≤ 75	1

Mid-Term Evaluation

MID-1 EXAM	**Description**	**Marks**	**Total**
1. Objective Type	20 Questions 20 x 0.5	10	
2. Subjective Type	Module -I : 2 Questions 05 x 4 Module -II : 2 Questions Module -III : 1 Questions	20	
3. Assignment		5	
4. Attendance	Refer Previous Table	5	**40**
MID-2 EXAM	**Description**	**Marks**	
1. Objective Type	20 Questions 20 x 0.5	10	
2. Subjective Type	Module -III : 1 Questions 05 x 4 Module -IV : 2 Questions Module -V : 2 Questions	20	
3. Assignment		5	
4. Attendance	Refer Previous Table	5	**40**

70% of the best performed plus 30% of the other shall be taken as the final marks secured by the Student towards Continuous Internal Evaluation in that Theory Subject

B) Semester End Examination (SEE)

The distribution of marks is as given below

Semester End Examination - UG			
Type of Questions	No. of Questions	Marks per Question	Total
Choice Questions: For each question there will be an 'either or choice', which means that there will be two questions from each module and the student should answer either of the two questions.	5	14	70

Faculty **Course Coordinator** **HOD**

MODULE-I

THREE PHASE INDUCTION MOTOR

The most common type of AC motor being used throughout the work today is the "Induction Motor". Applications of three-phase induction motors of size varying from half a kilowatt to thousands of kilowatts are numerous. They are found everywhere from a small workshop to a large manufacturing industry.

The advantages of three-phase AC induction motor are listed below:

1) Simple design
2) Rugged construction
3) Reliable operation
4) Low initial cost
5) Easy operation and simple maintenance
6) Simple control gear for starting and speed control
7) High efficiency.

Induction motor is originated in the year 1891 with crude construction (The induction machine principle was invented by NIKOLA TESLA in 1888.). Then an improved construction with distributed stator windings and a cage rotor was built.

The slip ring rotor was developed after a decade or so. Since then a lot of improvement has taken place on the design of these two types of induction motors. Lot of research work has been carried out to improve its power factor and to achieve suitable methods of speed control.

Types And Construction Of Three Phase Induction Motor

Three phase induction motors are constructed into two major types:

1) Squirrel cage Induction Motors
2) Slip ring Induction Motors

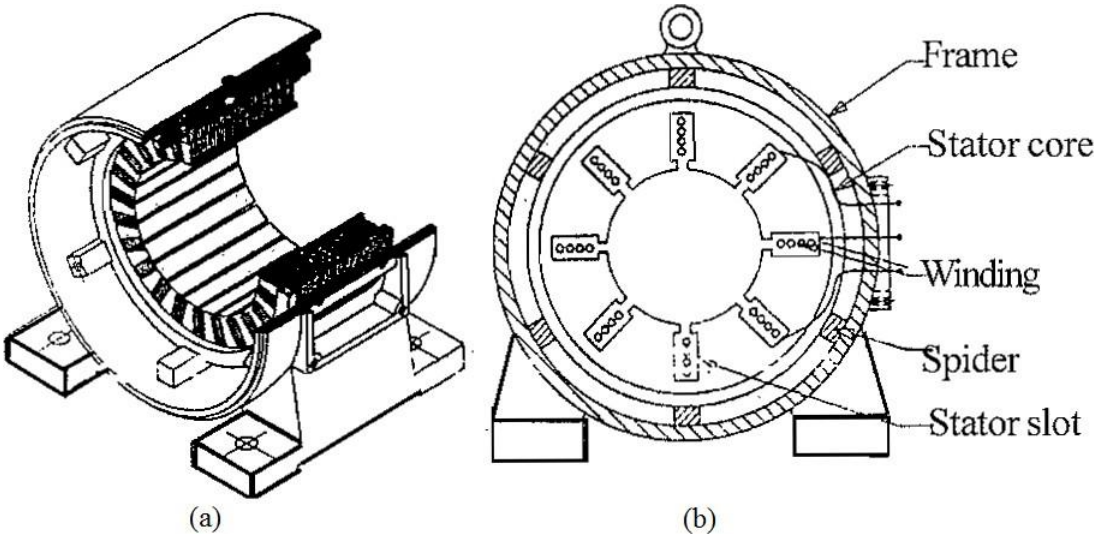
1) Squirrel cage Induction Motors

Stator Construction

The induction motor stator resembles the stator of a revolving field, three phase alternator. The stator or the stationary part consists of three phase winding held in place in the slots of a laminated steel core which is enclosed and supported by a cast iron or a steel frame as shown in Fig: 1.1(a).

The phase windings are placed 120 electrical degrees apart and may be connected in either star or delta externally, for which six leads are brought out to a terminal box mounted on the frame of the motor.

When the stator is energized from a three phase voltage it will produce a rotating magnetic field in the stator core.



(a) (b)

Fig: 1.1

Rotor Construction

The rotor of the squirrel cage motor shown in Fig: 1.1(b) contains no windings. Instead it is a cylindrical core constructed of steel laminations with conductor bars mounted parallel to the shaft and embedded near the surface of the rotor core.

These conductor bars are short circuited by an end rings at both end of the rotor core. In large machines, these conductor bars and the end rings are made up of copper with the bars brazed or welded to the end rings shown in Fig: 1.1(b).In small machines the conductor bars and end rings are sometimes made of aluminum with the bars and rings cast in as part of the rotor core. Actually the entire construction (bars and end-rings) resembles a squirrel cage, from which the name is derived.

The rotor or rotating part is not connected electrically to the power supply but has voltage induced in it by transformer action from the stator. For this reason, the stator is sometimes called the primary and the rotor is referred to as the secondary of the motor since the motor operates on the principle of induction and as the construction of the rotor with the bars and end rings resembles a squirrel cage, the squirrel cage induction motor is used.

The rotor bars are not insulated from the rotor core because they are made of metals having less resistance than the core. The induced current will flow mainly in them. Also the rotor bars are usually not quite parallel to the rotor shaft but are mounted in a slightly skewed position. This feature tends to produce a more uniform rotor field and torque. Also it helps to reduce some of the internal magnetic noise when the motor is running.

End Shields

The function of the two end shields is to support the rotor shaft. They are fitted with bearings and attached to the stator frame with the help of studs or bolts attention.

2) Slip ring Induction Motors.

Stator Construction

The construction of the slip ring induction motor is exactly similar to the construction of squirrel cage induction motor. There is no difference between squirrel cage and slip ring motors.

Rotor Construction

The rotor of the slip ring induction motor is also cylindrical or constructed of lamination.

Squirrel cage motors have a rotor with short circuited bars whereas slip ring motors have wound rotors having "three windings" each connected in star.

The winding is made of copper wire. The terminals of the rotor windings of the slip ring motors are brought out through slip rings which are in contact with stationary brushes as shown in Fig: 1.2.

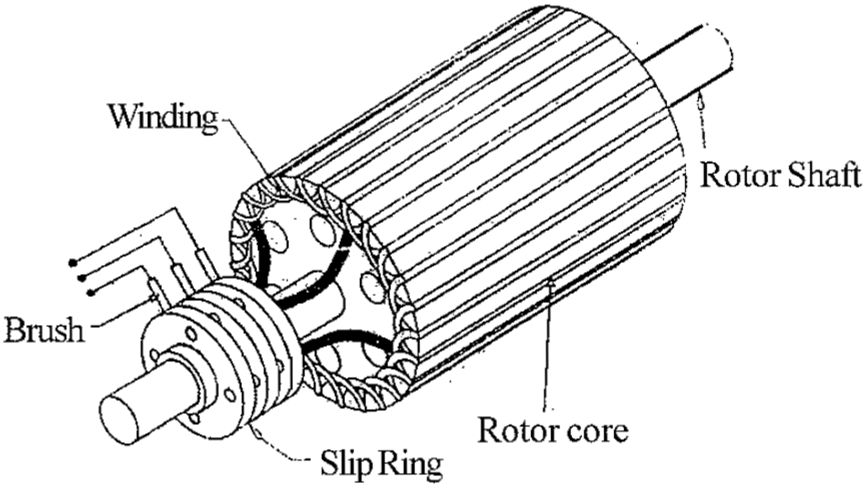


Fig: 1.2

The advantages of the slipring motor are

1) It has susceptibility to speed control by regulating rotor resistance.
2) High starting torque of 200 to 250% of full load value.
3) Low starting current of the order of 250 to 350% of the full load current.

Hence slip ring motors are used where one or more of the above requirements are to be met.

Comparison of squirrel cage and slip ring motor

Sl.No.	Property	Squirrel cage motor	Slip ring motor
1.	Rotor Construction	Bars are used in rotor. Squirrel cage motor is very simple, rugged and long lasting. No slip rings and brushes	Winding wire is to be used. Wound rotor required attention. Slip ring and brushes are needed also need frequent maintenance.
2.	Starting	Can be started by D.O.L., star-delta, auto transformer starters	Rotor resistance starter is required.
3.	Starting torque	Low	Very high
4.	Starting Current	High	Low
5.	Speed variation	Not easy, but could be varied in large steps by pole changing or through smaller incremental steps through thyristors or by frequency variation.	Easy to vary speed. Speed change is possible by inserting rotor resistance using thyristors or by using frequency variation injecting emf in the rotor circuit cascading.
6.	Maintenance	Almost ZERO maintenance	Requires frequent maintenance
7.	Cost	Low	High

Principle of operation

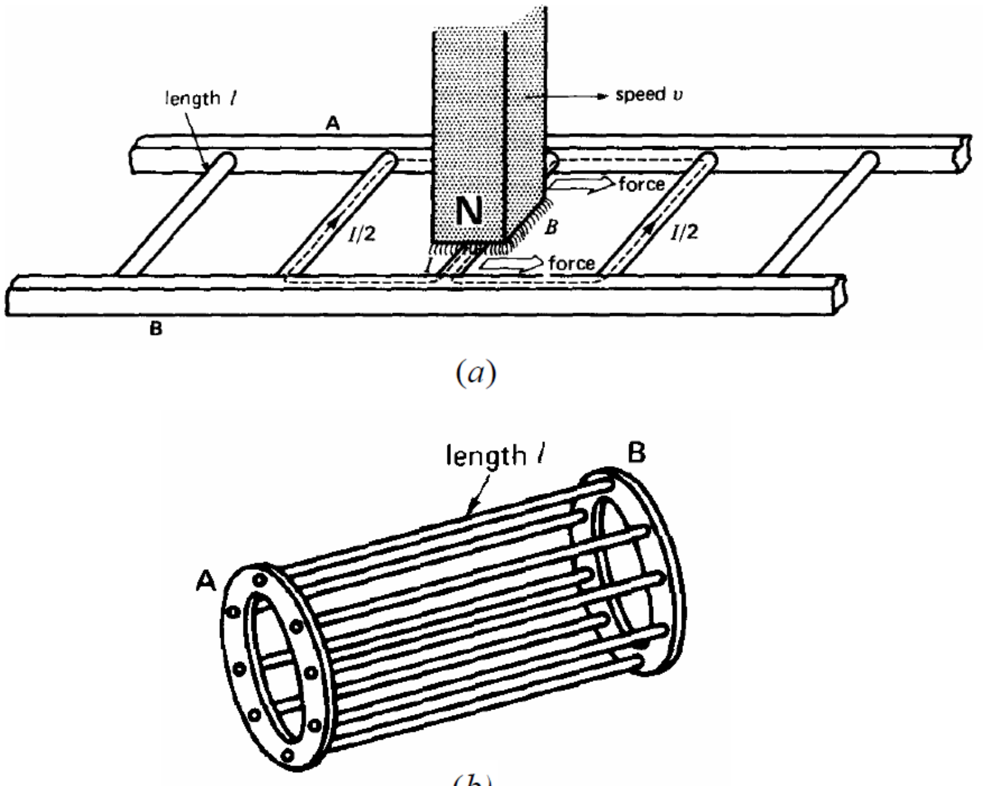
The operation of a 3-phase induction motor is based upon the application of Faraday Law and the Lorentz force on a conductor. The behavior can readily be understood by means of the following example.

Consider a series of conductors of length l, whose extremities are short-circuited by two bars A and B (Fig.1.3 a). A permanent magnet placed above this conducting ladder, moves rapidly to the right at a speed v, so that its magnetic field B sweeps across the conductors. The following sequence of events then takes place:

A voltage E = Blv is induced in each conductor while it is being cut by the flux (Faraday law).
The induced voltage immediately produces a current I, which flows down the conductor underneath the pole face, through the end-bars, and back through the other conductors.

Because the current carrying conductor lies in the magnetic field of the permanent magnet, it experiences a mechanical force (Lorentz force).

The force always acts in a direction to drag the conductor along with the magnetic field. If the conducting ladder is free to move, it will accelerate toward the right. However, as it picks up speed, the conductors will be cut less rapidly by the moving magnet, with the result that the induced voltage E and the current I will diminish. Consequently, the force acting on the conductors wilt also decreases. If the ladder were to move at the same speed as the magnetic field, the induced voltage E, the current I, and the force dragging the ladder along would all become zero.



(a)

(b)

Fig: 1.3

In an induction motor the ladder is closed upon itself to form a squirrel-cage (Fig.1.3b) and the moving magnet is replaced by a rotating field. The field is produced by the 3-phase currents that flow in the stator windings.

Rotating magnetic field and induced voltages

Consider a simple stator having 6 salient poles, each of which carries a coil having 5 turns (Fig.1.4). Coils that are diametrically opposite are connected in series by means of three jumpers

that respectively connect terminals a-a, b-b, and c-c. This creates three identical sets of windings AN, BN, CN, which are mechanically spaced at 120 degrees to each other. The two coils in each winding produce magneto motive forces that act in the same direction.

The three sets of windings are connected in way, thus forming a common neutral N. Owing to the perfectly symmetrical arrangement, the line to neutral impedances are identical. In other words, as regards terminals A, B, C, the windings constitute a balanced 3-phase system.

For a two-pole machine, rotating in the air gap, the magnetic field (i.e., flux density) being sinusoid ally distributed with the peak along the centre of the magnetic poles. The result is illustrated in Fig.1.5. The rotating field will induce voltages in the phase coils aa', bb', and cc'. Expressions for the induced voltages can be obtained by using Faraday laws of induction.

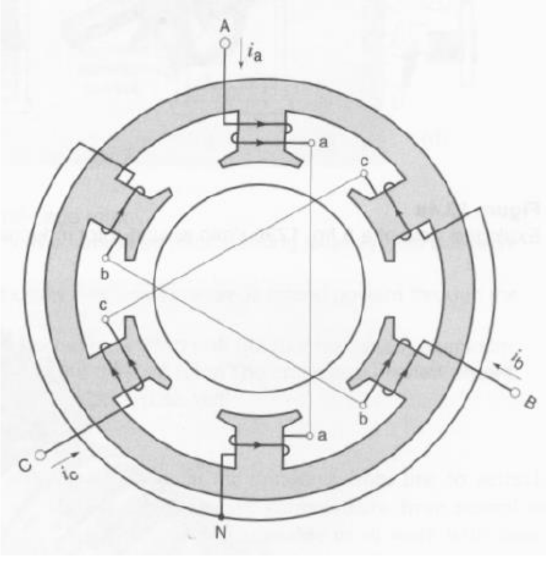


Fig: 1.4

Elementary stator having terminals A, B, C connected to a 3-phase source (not shown). Currents flowing from line to neutral are considered to be positive.

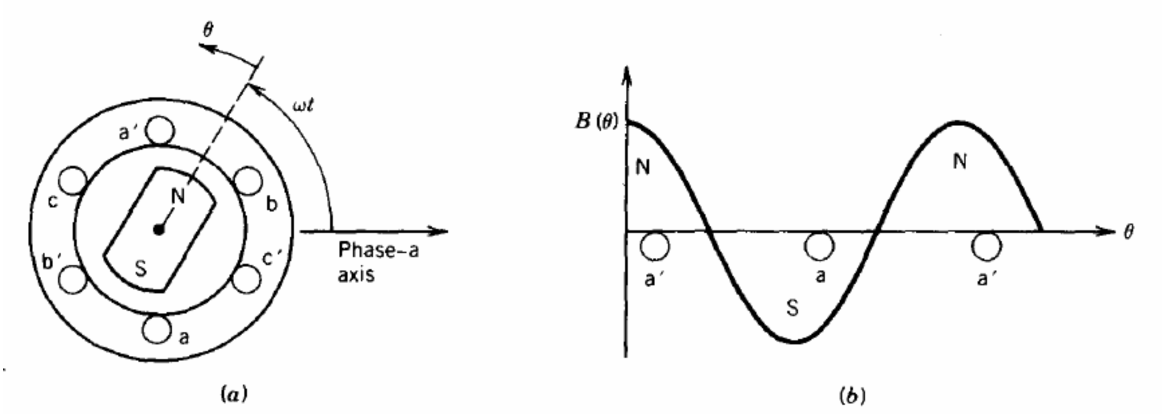


Fig: 1.5 Air gap flux density distribution.

Let us consider that the phase coils are full-pitch coils of N turns (the coil sides of each phase are 180 electrical degrees apart as shown in Fig.1.5). It is obvious that as the rotating field moves (or the magnetic poles rotate) the flux linkage of a coil will vary. The flux linkage for coil aa' will be maximum.

($= N\phi_P \; at \; \omega t = 0^o$) (Fig.3.5a) and zero at $\omega t = 90^o$. The flux linkage $\lambda_a(\omega t)$ will vary as the cosine of the angle ωt.

Hence,

$$\lambda_a(\omega t) = N\phi_p \cos \omega t$$

Therefore, the voltage induced in phase coil **aa'** is obtained from *Faraday law* as:

$$e_a = -\frac{d\lambda_a(\omega t)}{dt} = \omega N\phi_p \sin \omega t = E_{\max} \sin \omega t$$

The voltages induced in the other phase coils are also sinusoidal, but phase-shifted from each other by 120 electrical degrees. Thus,

$$e_b = E_{\max} \sin(\omega t - 120)$$

$$e_c = E_{\max} \sin(\omega t + 120).$$

Where f is the frequency in hertz. Above equation has the same form as that for the induced voltage in transformers. However, ØP represents the flux per pole of the machine.

the *rms* value of the induced voltage is:

$$E_{rms} = \frac{\omega N\phi_p}{\sqrt{2}} = \frac{2\pi f}{\sqrt{2}} N\phi_p = 4.44 fN\phi_p$$

The above equation also shows the rms voltage per phase. The N is the total number of series turns per phase with the turns forming a concentrated full-pitch winding. In an actual AC machine each phase winding is distributed in a number of slots for better use of the iron and copper and to improve the waveform. For such a distributed winding, the EMF induced in various coils placed in different slots are not in time phase, and therefore the phasor sum of the EMF is less than their numerical sum when they are connected in series for the phase winding. A reduction factor K_W, called the winding factor, must therefore be applied. For most three-phase machine windings K_W is about 0.85 to 0.95.

Therefore, for a distributed phase winding, the rms voltage per phase is

$$E_{rms} = 4.44 f N_{ph} \varphi_p K_W$$

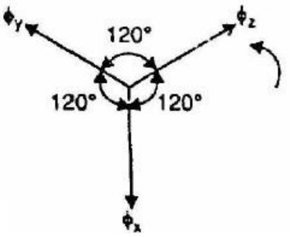
Where N_{ph} is the number of turns in series per phase.

Alternate analysis for rotating magnetic field

When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced. This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator. For this reason, it is called a rotating Held. It can be shown that magnitude of this rotating field is constant and is equal to 1.5 m where m is the maximum flux due to any phase.

To see how rotating field is produced, consider a 2-pole, 3-phase winding as shown in Fig. 1.6 (i). The three phases X, Y and Z are energized from a 3-phase source and currents in these phases are indicated as Ix, Iy and Iz [See Fig. 1.6 (ii)]. Referring to Fig. 1.6 (ii), the fluxes produced by these currents are given by:

$$\phi_x = \phi_m \sin \omega t$$
$$\phi_y = \phi_m \sin (\omega t - 120^\circ)$$
$$\phi_z = \phi_m \sin (\omega t - 240^\circ)$$



Here □m is the maximum flux due to any phase. Above figure shows the phasor diagram of the three fluxes. We shall now prove that this 3-phase supply produces a rotating field of constant magnitude equal to 1.5 □m.

At instant 1 [See Fig. 1.6 (ii) and Fig. 1.6 (iii)], the current in phase X is zero and currents in phases Y and Z are equal and opposite. The currents are flowing outward in the top conductors and inward in the bottom conductors. This establishes a resultant flux towards right. The magnitude of the resultant flux is constant and is equal to 1.5 □m as proved under:

At instant 1, ωt = 0°. Therefore, the three fluxes are given by;

$$\phi_x = 0; \qquad \phi_y = \phi_m \sin(-120°) = -\frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_z = \phi_m \sin(-240°) = \frac{\sqrt{3}}{2}\phi_m$$

The phasor sum of $-\phi_y$ and ϕ_z is the resultant flux ϕ_r

So,

$$\text{Resultant flux, } \phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2} = 2 \times \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = 1.5\ \phi_m$$

At instant 2 [Fig: 1.7 (ii)], the current is maximum (negative) in □y phase Y and 0.5 maximum (positive) in phases X and Y. The magnitude of resultant flux is 1.5 □m as proved under:

At instant 2, □t = 30°. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 30° = \frac{\phi_m}{2}$$

$$\phi_y = \phi_m \sin(-90°) = -\phi_m$$

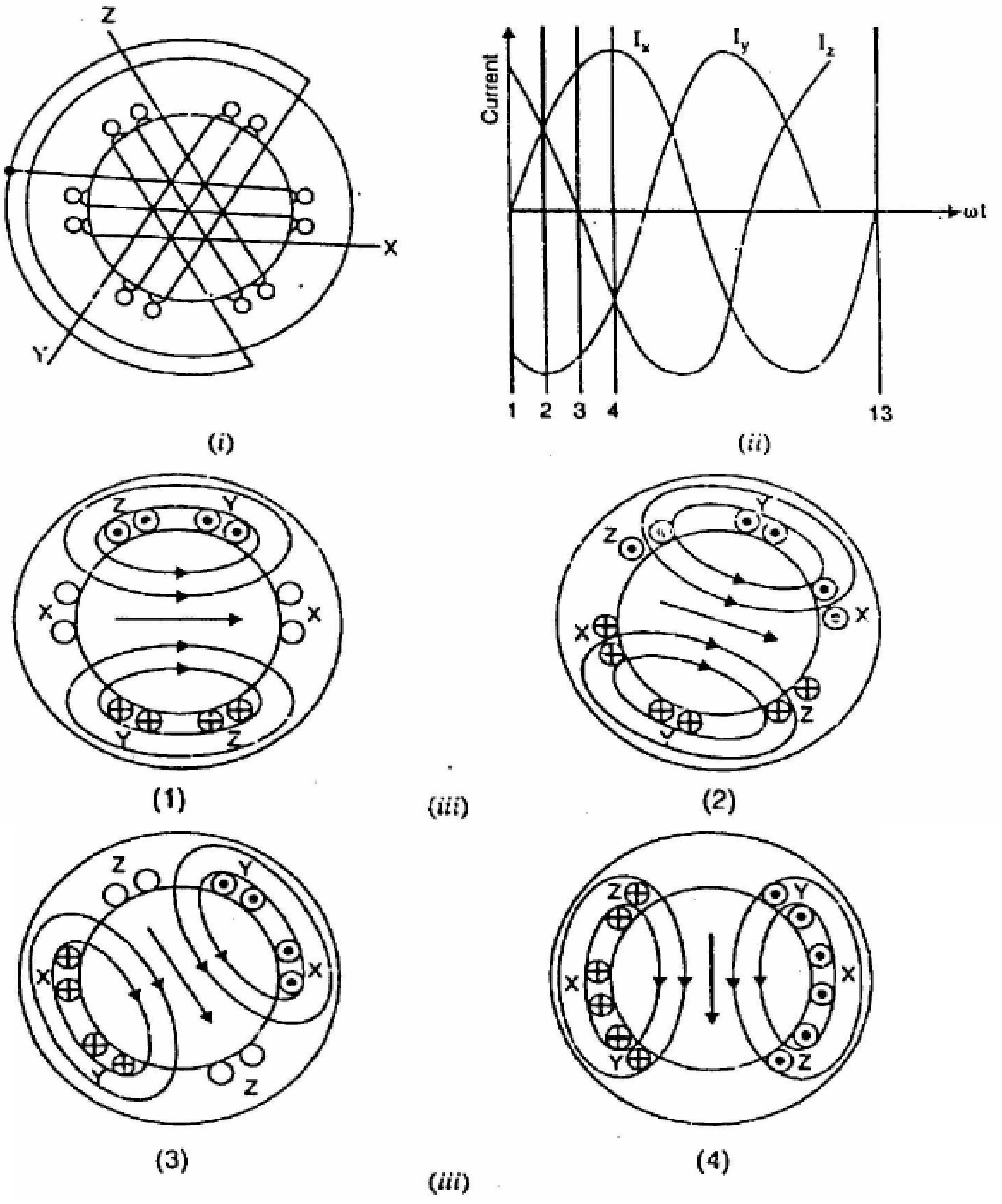
$$\phi_z = \phi_m \sin(-210°) = \frac{\phi_m}{2}$$

The phasor sum of ϕ_x, $-\phi_y$ and ϕ_z is the resultant flux ϕ_r

$$\text{Phasor sum of } \phi_x \text{ and } \phi_z,\ \phi'_r = 2 \times \frac{\phi_m}{2} \cos\frac{120°}{2} = \frac{\phi_m}{2}$$

$$\text{Phasor sum of } \phi'_r \text{ and } -\phi_y,\ \phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\ \phi_m$$

Note that resultant flux is displaced 30° clockwise from position 1.



(i) (ii)

(1) (iii) (2)

(3) (iii) (4)

Fig: 1.6

At instant 3[Fig: 1.7 (iii)], current in phase Z is zero and the currents in phases X and Y are equal and opposite (currents in phases X and Y arc 0.866 □ max. value). The magnitude of resultant flux is 1.5 □m as proved under:

At instant 3, $\omega t = 60°$. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 60° = \frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_y = \phi_m \sin(-60°) = -\frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_z = \phi_m \sin(-180°) = 0$$

The resultant flux ϕ_r is the phasor sum of ϕ_x and $-\phi_y$ $(\because\ \phi_z = 0)$.

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2} = 1.5\ \phi_m$$

Note that resultant flux is displaced 60° clockwise from position 1.

At instant 4 [Fig: 1.7 (iv)], the current in phase X is maximum (positive) and the currents in phases V and Z are equal and negative (currents in phases V and Z are 0.5 □ max. value). This establishes a resultant flux downward as shown under:

It follows from the above discussion that a 3-phase supply produces a rotating field of constant value (= 1.5 □m, where □m is the maximum flux due to any phase).

Speed of rotating magnetic field

The speed at which the rotating magnetic field revolves is called the synchronous speed (Ns). Referring to Fig. 1.6 (ii), the time instant 4 represents the completion of one-quarter cycle of alternating current Ix from the time instant 1. During this one quarter cycle, the field has rotated through 90°. At a time instant represented by 13 [Fig. 1.6 (ii)] or one complete cycle of current Ix from the origin, the field has completed one revolution. Therefore, for a 2-pole stator winding, the field makes one revolution in one cycle of current. In a 4-pole stator winding, it can be shown that the rotating field makes one revolution in two cycles of current. In general, fur P poles, the rotating field

$$\therefore \quad \text{Cycles of current} = \frac{P}{2} \times \text{revolutions of field}$$

or $$\text{Cycles of current per second} = \frac{P}{2} \times \text{revolutions of field per second}$$

Since revolutions per second is equal to the revolutions per minute (N_s) divided by 60 and the number of cycles per second is the frequency f,

$$\therefore \quad f = \frac{P}{2} \times \frac{N_s}{60} = \frac{N_s P}{120}$$

or $$N_s = \frac{120\,f}{P}$$

makes one revolution in P/2 cycles of current.

The speed of the rotating magnetic field is the same as the speed of the alternator that is supplying power to the motor if the two have the same number of poles. Hence the magnetic flux is said to rotate at synchronous speed.

Direction of rotating magnetic field

The phase sequence of the three-phase voltage applied to the stator winding in Fig. 1.6 (ii) is X- Y-Z. If this sequence is changed to X-Z-Y, it is observed that direction of rotation of the field is reversed i.e., the field rotates counter clockwise rather than clockwise. However, the number of poles and the speed at which the magnetic field rotates remain unchanged. Thus it is necessary only to change the phase sequence in order to change the direction of rotation of the magnetic field. For a three-phase supply, this can be done by interchanging any two of the three lines. As we shall see, the rotor in a 3-phase induction motor runs in the same direction as the rotating magnetic field. Therefore, the direction of rotation of a 3-phase induction motor can be reversed by interchanging any two of the three motor supply lines.

Slip

We have seen above that rotor rapidly accelerates in the direction of rotating field. In practice, the rotor can never reach the speed of stator flux. If it did, there would be no relative speed between the stator field and rotor conductors, no induced rotor currents and, therefore, no torque to drive the rotor. The friction and windage would immediately cause the rotor to slow down. Hence, the rotor speed (N) is always less than the suitor field speed (Ns). This difference in speed depends upon load on the motor. The difference between the synchronous speed Ns of the rotating stator field and the actual rotor speed N is called slip. It is usually expressed as a percentage of synchronous speed i.e.

$$\%\text{ age slip, } s = \frac{N_s - N}{N_s} \times 100$$

(i) The quantity $N_s - N$ is sometimes called slip speed.

(ii) When the rotor is stationary (i.e., $N = 0$), slip, $s = 1$ or 100 %.

(iii) In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% so that it is essentially a constant-speed motor.

Rotor current frequency

The frequency of a voltage or current induced due to the relative speed between a vending and a magnetic field is given by the general formula;

(ii) As the rotor picks up speed, the relative speed between the rotating flux and the rotor decreases. Consequently, the slip s and hence rotor current frequency decreases.

Phasor diagram of three phase induction motor

In a 3-phase induction motor, the stator winding is connected to 3-phase supply and the rotor winding is short-circuited. The energy is transferred magnetically from the stator winding to the short-circuited, rotor winding. Therefore, an induction motor may be considered to be a transformer with a rotating secondary (short-circuited). The stator winding corresponds to transformer primary and the rotor finding corresponds to transformer secondary. In view of the similarity of the flux and voltage conditions to those in a transformer, one can expect that the equivalent circuit of an induction motor will be similar to that of a transformer. Fig. 3.8 shows the equivalent circuit per phase for an induction motor. Let discuss the stator and rotor circuits separately.

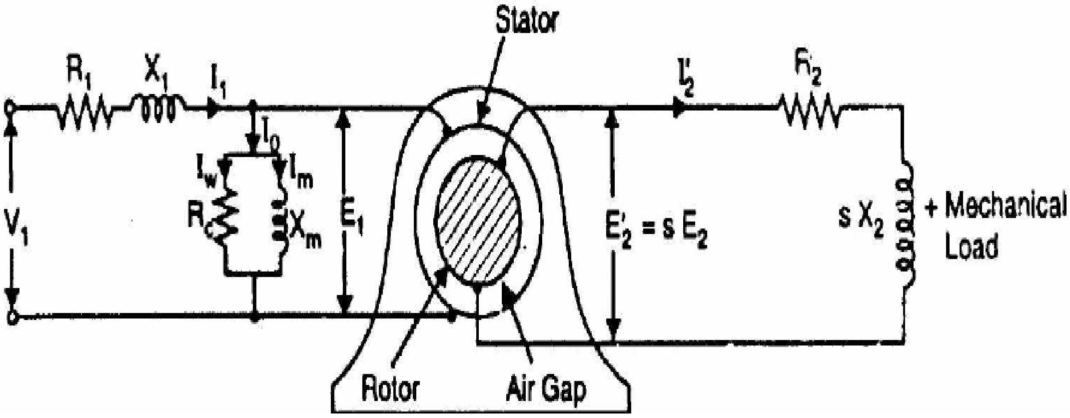


Fig: 1.8

Stator circuit. In the stator, the events are very similar to those in the transformer primary. The applied voltage per phase to the stator is V1 and R1and X1 are the stator resistance and leakage reactance per phase respectively. The applied voltage V1 produces a magnetic flux which links the stator winding (i.e., primary) as well as the rotor winding (i.e., secondary). As a result, self- induced e.m.f. E1 is induced in the stator winding and mutually induced e.m.f.

E'2(= s E2 = s K E1 where K is transformation ratio) is induced in the rotor winding. The flow of stator current I1 causes voltage drops in R1 and X1.

□ V1 □ □E1 □ I1 (R1□ j X1) ...phasor sum

When the motor is at no-load, the stator winding draws a current I0. It has two components viz., which supplies the no-load motor losses and (ii) magnetizing component Im which sets up magnetic flux in the core and the air gap. The parallel combination of Rc and Xm, therefore, represents the no-load motor losses and the production of magnetic flux respectively.

□ I0 □ Iw □ Im

Rotor circuit. Here R2 and X2 represent the rotor resistance and standstill rotor reactance per phase respectively. At any slip s, the rotor reactance will be X2 .The induced voltage/phase in the rotor is E'2 = s E2 = s K E1. Since the rotor winding is short-circuited, the whole of e.m.f. E'2 is used up in circulating the rotor current I'2.

□ E'2 □ I'2 (R2 □ j s X2)

The rotor current I'2 is reflected as I"2 (= K I'2) in the stator. The phasor sum of I"2 and I0 gives the stator current I1.

It is important to note that input to the primary and output from the secondary of a transformer are electrical. However, in an induction motor, the inputs to the stator and rotor are electrical but the output from the rotor is mechanical. To facilitate calculations, it is desirable and necessary to replace the mechanical load by an equivalent electrical load. We then have the transformer equivalent circuit of the induction motor.

It may be noted that even though the frequencies of stator and rotor currents are different, yet the magnetic fields due to them rotate at synchronous speed Ns. The stator currents produce a magnetic flux which rotates at a speed Ns. At slip s, the speed of rotation of the rotor field relative to the rotor surface in the direction of rotation of the rotor is

$$= \frac{120\ f'}{P} = \frac{120\ s\ f}{P} = s\ N_s$$

But the rotor is revolving at a speed of N relative to the stator core. Therefore, the speed of rotor field relative to stator core

$$= sN_s + N = (N_s - N) + N = N_s$$

Thus no matter what the value of slip s, the stator and rotor magnetic fields are synchronous with each other when seen by an observer stationed in space. Consequently, the 3-phase induction motor can be regarded as being equivalent to a transformer having an air-gap separating the iron portions of the magnetic circuit carrying the primary and secondary windings. Fig. 1.9 shows the phasor diagram of induction motor.

Equivalent circuit of three phase induction motor

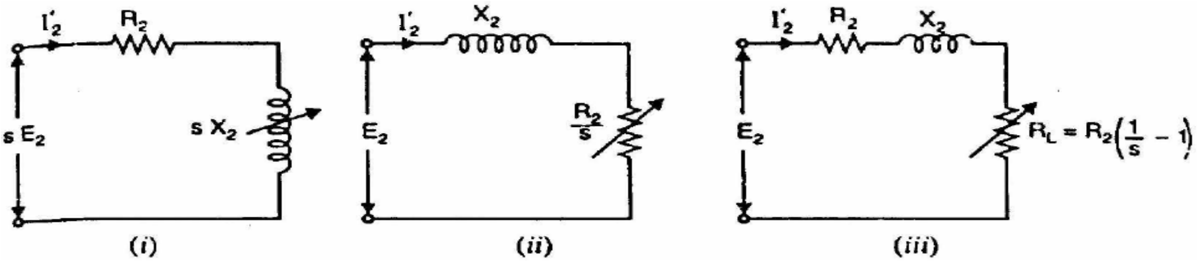
Fig. 1.10 (i) shows the equivalent circuit per phase of the rotor at slip s. The rotor phase current is given by;

$$I'_2 = \frac{s\,E_2}{\sqrt{R_2^2 + (s\,X_2)^2}}$$

Mathematically, this value is unaltered by writing it as:

$$I'_2 = \frac{E_2}{\sqrt{(R_2/s)^2 + (X_2)^2}}$$

As shown in Fig. 1.10 (ii), we now have a rotor circuit that has a fixed reactance X2 connected in series with a variable resistance R2/s and supplied with constant voltage E2. Note that Fig. 3.10 transfers the variable to the resistance without altering power or power factor conditions.



(i) (ii) (iii)

Fig: 1.10

The quantity R_2/s is greater than R_2 since s is a fraction. Therefore, R_2/s can be divided into a fixed part R_2 and a variable part $(R_2/s - R_2)$ i.e.,

$$\frac{R_2}{s} = R_2 + R_2\left(\frac{1}{s} - 1\right)$$

(i) The first part R_2 is the rotor resistance/phase, and represents the rotor Cu loss.

(ii) The second part $R_2\left(\frac{1}{s} - 1\right)$ is a variable-resistance load. The power delivered to this load represents the total mechanical power developed in the rotor. Thus mechanical load on the induction motor can be replaced by a variable-resistance load of value $R_2\left(\frac{1}{s} - 1\right)$. This is

$$\therefore \quad R_L = R_2\left(\frac{1}{s} - 1\right)$$

Fig. 1.10 (iii) shows the equivalent rotor circuit along with load resistance RL.

Now Fig: 1.11 shows the equivalent circuit per phase of a 3-phase induction motor. Note that mechanical load on the motor has been replaced by an equivalent electrical resistance RL given by;

$$R_L = R_2\left(\frac{1}{s} - 1\right) \qquad \text{--------------------------------(i)}$$

The circuit shown in Fig. 1.11 is similar to the equivalent circuit of a transformer with secondary load equal to R2 given by Eq. (i). The rotor e.m.f. in the equivalent circuit now depends only on the transformation ratio K (= E2/E1).

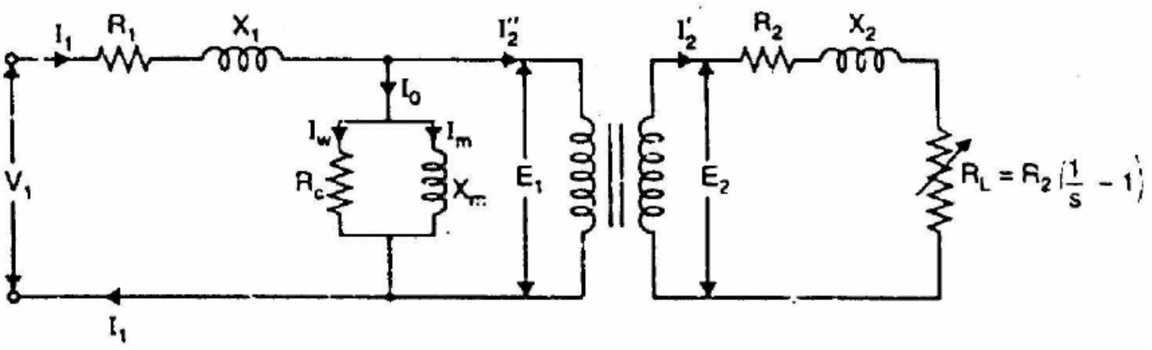


Fig: 1.11

Therefore; induction motor can be represented as an equivalent transformer connected to a variable-resistance load RL given by Eq. (i). The power delivered to RL represents the total mechanical power developed in the rotor. Since the equivalent circuit of Fig. 1.11 is that of a transformer, the secondary (i.e., rotor) values can be transferred to primary (i.e., stator) through the appropriate use of transformation ratio K. Recall that when shifting resistance/reactance from secondary to primary, it should be divided by K2 whereas current should be multiplied by K. The equivalent circuit of an induction motor referred to primary

Note that the element (i.e., R'L) enclosed in the dotted box is the equivalent electrical resistance related to the mechanical load on the motor. The following points may be noted from the equivalent circuit of the induction motor:

At no-load, the slip is practically zero and the load R'L is infinite. This condition resembles that in a transformer whose secondary winding is open-circuited.

At standstill, the slip is unity and the load R'L is zero. This condition resembles that in a transformer whose secondary winding is short-circuited.

When the motor is running under load, the value of R'L will depend upon the value of the slip s. This condition resembles that in a transformer whose secondary is supplying variable and purely resistive load.

The equivalent electrical resistance R'L related to mechanical load is slip or speed dependent. If the slip s increases, the load R'L decreases and the rotor current increases and motor will develop more mechanical power. This is expected because the slip of the motor increases with the increase of load on the motor shaft.

Cogging and crawling of induction motor

Crawling of induction motor

Sometimes, squirrel cage induction motors exhibits a tendency to run at very slow speeds (as low as one-seventh of their synchronous speed). This phenomenon is called as crawling of an induction motor.

This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave. Instead, it is a complex wave consisting a fundamental wave and odd harmonics like 3rd, 5th, 7th etc. The fundamental wave revolves synchronously at synchronous speed Ns whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at Ns/3, Ns/5, Ns/7 speeds respectively. Hence, harmonic torques are also developed in addition with fundamental torque

3rd harmonics are absent in a balanced 3-phase system. Hence 3rdd harmonics do not produce rotating field and torque. The total motor torque now consist three components as: (i) the fundamental torque with synchronous speed Ns, (ii) 5th harmonic torque with synchronous speed

Ns/5, (iv) 7th harmonic torque with synchronous speed Ns/7 (provided that higher harmonics are neglected).

Now, 5th harmonic currents will have phase difference of
5 X 120 = 600° =2 X 360 - 120 = -120°.

Hence the revolving speed set up will be in reverse direction with speed Ns/5. The small amount of 5th harmonic torque produces breaking action and can be neglected.

The 7th harmonic currents will have phase difference of
7 X 120 = 840° = 2 X 360 +120 = + 120°.

Hence they will set up rotating field in forward direction with synchronous speed equal to Ns/7. If we neglect all the higher harmonics, the resultant torque will be equal to sum of fundamental torque and 7th harmonic torque. 7^{th} harmonic torque reaches its maximum positive value just before$1/7^{th}$ of Ns. If the mechanical load on the shaft involves constant load torque, the torque developed by the motor may fall below this load torque. In this case, motor will not accelerate up to its normal speed, but it will run at a speed which is nearly 1/7th of its normal speed as shown in Fig: 1.40. This phenomenon is called as crawling of induction motors.

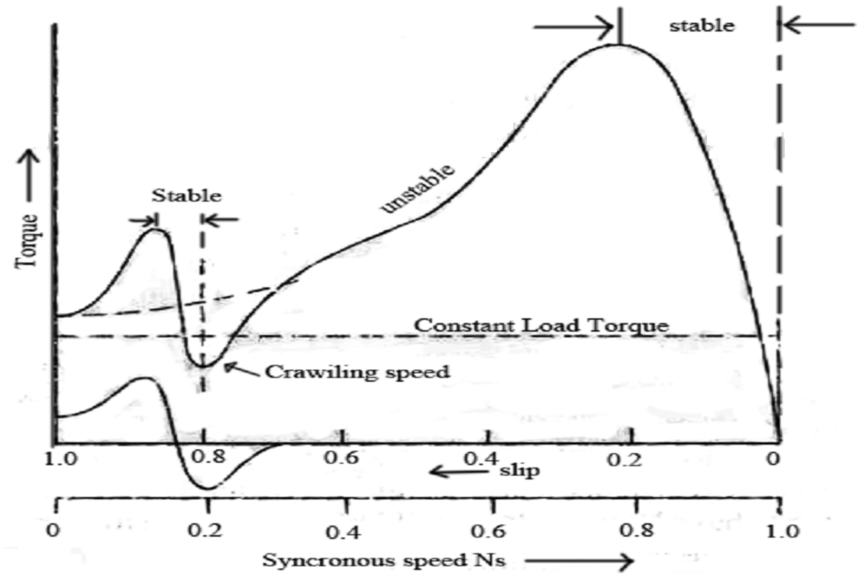


Fig: 1.40

Cogging (Magnetic Locking or Teeth Locking) of induction motor

Sometimes, the rotor of a squirrel cage induction motor refuses to start at all, particularly if the supply voltage is low. This happens especially when number of rotor teeth is equal to number of stator teeth, because of magnetic locking between the stator teeth and the rotor teeth. When the rotor teeth and stator teeth face each other, the reluctance of the magnetic path is minimum that is why the rotor tends to remain fixed. This phenomenon is called cogging or magnetic locking of induction motor.

Power stages in an induction motor

The input electric power fed to the stator of the motor is converted into mechanical power at the shaft of the motor. The various losses during the energy conversion are:

1) Fixed losses
2) Stator iron loss
3) Friction and windage loss

4) The rotor iron loss is negligible because the frequency of rotor currents under normal running condition is small.

5) Variable losses
6) Stator copper loss
7) Rotor copper loss

Fig: 1.37 shows how electric power fed to the stator of an induction motor suffers losses and finally converted into mechanical power.

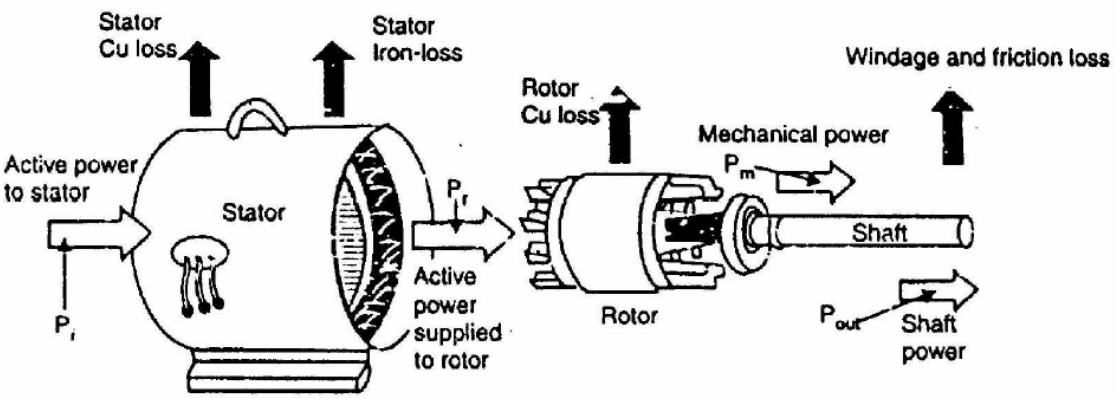


Fig: 1.37

The following points may be noted from the above diagram:

Stator input, Pi = Stator output + Stator losses= Stator output + Stator Iron loss + Stator Cu loss
Rotor input, Pr = Stator output

It is because stator output is entirely transferred to the rotor through air-gap by electromagnetic induction.

Mechanical power available, Pm = Pr - Rotor Cu loss

This mechanical power available is the gross rotor output and will produce a gross torque Tg.

Mechanical power at shaft, Pout = Pm - Friction and windage loss Mechanical power available at the shaft produces a shaft torque Tsh.

Clearly, Pm - Pout = Friction and windage loss.

MODULE-II

PERFORMANCE OF INDUCTION MOTORS

Rotor input

Fig: 2.1 shows how electric power fed to the stator of an induction motor suffers losses and finally converted into mechanical power.

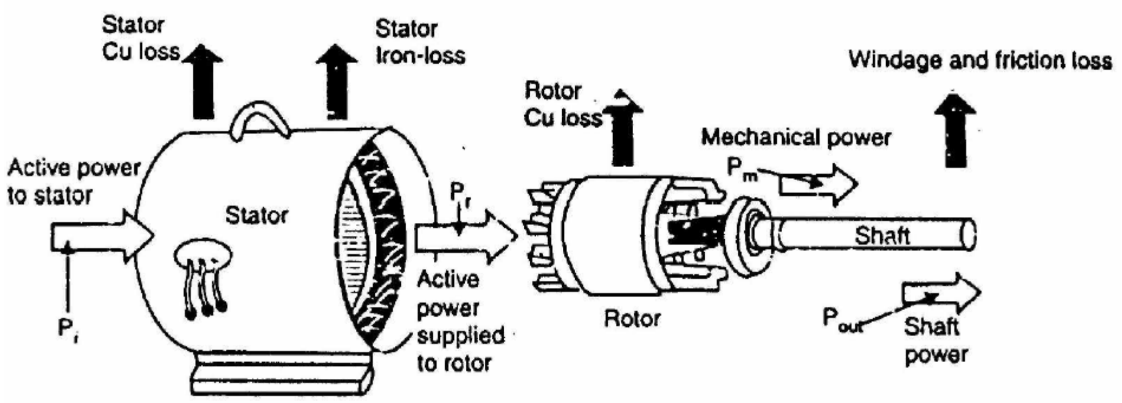


Fig: 2.1

The following points may be noted from the above diagram:

Stator input, Pi = Stator output + Stator losses = Stator output + Stator Iron loss + Stator Cu loss

Rotor input, Pr = Stator output

It is because stator output is entirely transferred to the rotor through air-gap by electromagnetic induction.

Mechanical power available, Pm = Pr - Rotor Cu loss

This mechanical power available is the gross rotor output and will produce a gross torque Tg.

Mechanical power at shaft, Pout = Pm - Friction and windage loss Mechanical power available at the shaft produces a shaft torque Tsh.

Clearly, Pm - Pout = Friction and windage loss.

Torque equations

The gross torque Tg developed by an induction motor is given by;

$$T_g = \frac{\text{Rotor input}}{2\pi\ N_s} \qquad \text{... } N_s \text{ is r.p.s.}$$

$$= \frac{60 \times \text{Rotor input}}{2\pi\ N_s} \qquad \text{... } N_s \text{ is r.p.s.}$$

Now $\quad \text{Rotor input} = \dfrac{\text{Rotor Cu loss}}{s} = \dfrac{3(I'_2)^2 R_2}{s} \qquad \text{(i)}$

As shown in Sec. 8.16, under running conditions,

$$I'_2 = \frac{s\ E_2}{\sqrt{R_2^2 + (s\ X_2)^2}} = \frac{s\ K\ E_1}{\sqrt{R_2^2 + (s\ X_2)^2}}$$

where $\quad K = \text{Transformation ratio} = \dfrac{\text{Rotor turns/phase}}{\text{Stator turns/phase}}$

$$\therefore \quad \text{Rotor input} = 3 \times \frac{s^2\ E_2^2 R_2}{R_2^2 + (s\ X_2)^2} \times \frac{1}{s} = \frac{3\ s\ E_2^2 R_2}{R_2^2 + (s\ X_2)^2}$$

(Putting me value of I'_2 in eq.(i))

Also $\quad \text{Rotor input} = 3 \times \dfrac{s^2\ K^2\ E_1^2 R_2}{R_2^2 + (s\ X_2)^2} \times \dfrac{1}{s} = \dfrac{3\ s\ K^2\ E_1^2 R_2}{R_2^2 + (s\ X_2)^2}$

(Putting me value of I'_2 in eq.(i))

Induction motor torque

$$\therefore \quad T_g = \frac{\text{Rotor input}}{2\pi\ N_s} = \frac{3}{2\pi\ N_s} \times \frac{s\ E_2^2 R_2}{R_2^2 + (s\ X_2)^2} \qquad \text{...in terms of } E_2$$

$$= \frac{3}{2\pi\ N_s} \times \frac{s\ K^2\ E_1^2 R_2}{R_2^2 + (s\ X_2)^2} \qquad \text{...in terms of } E_1$$

Note that in the above expressions of T_g, the values E_1, E_2, R_2 and X_2 represent the phase values.

The mechanical power P available from any electric motor can be expressed as:

$$P = \frac{2\pi N T}{60} \quad \text{watts}$$

where N = speed of the motor in r.p.m.
T = torque developed in N-m

$$\therefore \quad T = \frac{60}{2\pi}\frac{P}{N} = 9.55\frac{P}{N} \ \text{N - m}$$

If the gross output of the rotor of an induction motor is P_m and its speed is N r.p.m., then gross torque T developed is given by:

$$T_g = 9.55\frac{P_m}{N} \ \text{N - m}$$

Similarly, $T_{sh} = 9.55\frac{P_{out}}{N}$ N - m

Note. Since windage and friction loss is small, $T_g = T_{sh}$,. This assumption hardly leads to any significant error.

Rotor output

If T_g newton-metre is the gross torque developed and N r.p.m. is the speed of the rotor, then,

$$\text{Gross rotor output} = \frac{2\pi N T_g}{60} \quad \text{watts}$$

If there were no copper losses in the rotor, the output would equal rotor input and the rotor would run at synchronous speed Ns.

$$\therefore \quad \text{Rotor input} = \frac{2\pi N_s T_g}{60} \quad \text{watts}$$

$$\therefore \quad \text{Rotor Cu loss} = \text{Rotor input} - \text{Rotor output}$$

$$= \frac{2\pi\ T_g}{60}(N_s - N)$$

(i) $$\frac{\text{Rotor Cu loss}}{\text{Rotor input}} = \frac{N_s - N}{N_s} = s$$

$$\therefore \quad \text{Rotor Cu loss} = s \times \text{Rotor input}$$

(ii) Gross rotor output, P_m = Rotor input – Rotor Cu loss
= Rotor input – s × Rotor input

$$\therefore \quad P_m = \text{Rotor input } (1 - s)$$

(iii) $$\frac{\text{Gross rotor output}}{\text{Rotor input}} = 1 - s = \frac{N}{N_s}$$

(iv) $$\frac{\text{Rotor Cu loss}}{\text{Gross rotor output}} = \frac{s}{1 - s}$$

It is clear that if the input power to rotor is “Pr” then “SPr” is lost as rotor Cu loss and the remaining (1 - s) Pr is converted into mechanical power. Consequently, induction motor operating at high slip has poor efficiency.

Note.

$$\frac{\text{Gross rotor output}}{\text{Rotor input}} = 1 - s$$

If the stator losses as well as friction and windage losses arc neglected, then,

$$\text{Gross rotor output} = \text{Useful output}$$

$$\text{Rotor input} = \text{Stator input}$$

$$\therefore \quad \frac{\text{Useful output}}{\text{Stator output}} = 1 - s = \text{Efficiency}$$

Hence the approximate efficiency of an induction motor is 1 – s. Thus if the slip of an induction motor is 0.125, then its approximate efficiency is = 1 – 0.125 = 0.875 or 87.5%.

Rotor torque

The torque T developed by the rotor is directly proportional to:

(i) rotor current
(ii) rotor e.m.f.
(iii) power factor of the rotor circuit

$$\therefore \quad T \propto E_2 I_2 \cos\phi_2$$

or $$T = K E_2 I_2 \cos\phi_2$$

where I_2 = rotor current at standstill
E_2 = rotor e.m.f. at standstill
$\cos\phi_2$ = rotor p.f. at standstill

Note. The values of rotor e.m.f., rotor current and rotor power factor are taken for the given conditions.

Starting torque (t_s)

Let,

E_2 = rotor e.m.f. per phase at standstill

X_2 = rotor reactance per phase at standstill

R_2 = rotor resistance per phase

Rotor impedance/phase, $Z_2 = \sqrt{R_2^2 + X_2^2}$ ...at standstill

Rotor current/phase, $I_2 = \dfrac{E_2}{Z_2} = \dfrac{E_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

Rotor p.f., $\cos\phi_2 = \dfrac{R_2}{Z_2} = \dfrac{R_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

$$\therefore \quad \text{Starting torque, } T_s = K E_2 I_2 \cos\phi_2$$

$$= K E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$= \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

Generally, the stator supply voltage V is constant so that flux per pole □ set up by the stator is also fixed. This in turn means that e.m.f. E_2 induced in the rotor will be constant.

$$\therefore \quad T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} = \frac{K_1 R_2}{Z_2^2}$$

where K_1 is another constant.

It is clear that the magnitude of starting torque would depend upon the relative values of R_2 and X_2 i.e., rotor resistance/phase and standstill rotor reactance/phase.

It can be shown that $K = 3/2\pi N_s$.

$$\therefore \quad T_s = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Note that here N_s is in r.p.s.

Condition for maximum starting torque

It can be proved that starting torque will be maximum when rotor resistance/phase is equal to standstill rotor reactance/phase.

Now $$T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} \qquad \text{(i)}$$

Differentiating eq. (i) w.r.t. R_2 and equating the result to zero, we get,

$$\frac{dT_s}{dR_2} = K_1\left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2(2R_2)}{\left(R_2^2 + X_2^2\right)^2}\right] = 0$$

or $$R_2^2 + X_2^2 = 2R_2^2$$

or $$R_2 = X_2$$

Hence starting torque will be maximum when:

Rotor resistance/phase = Standstill rotor reactance/phase

Under the condition of maximum starting torque, □2 = 45° and rotor power factor is 0.707 lagging.

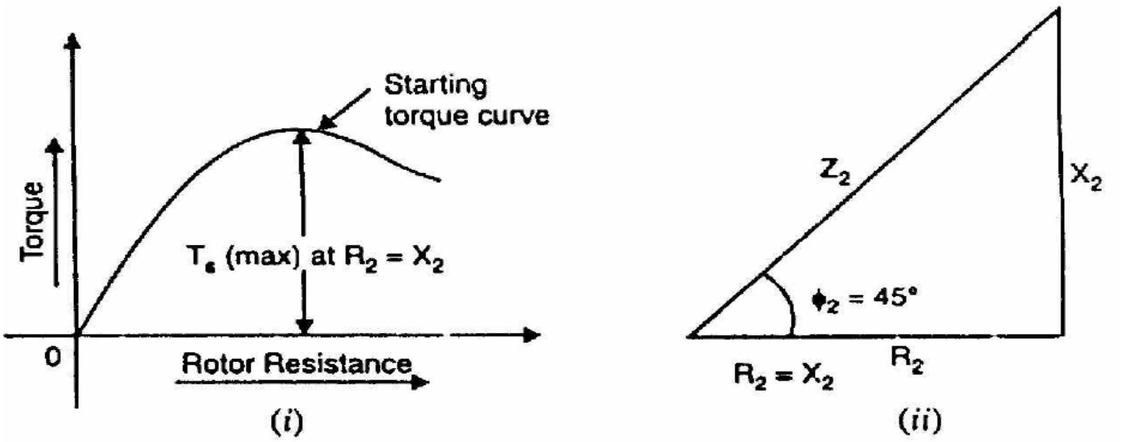


Fig: 2.14

Fig. 2.14 shows the variation of starting torque with rotor resistance. As the rotor resistance is increased from a relatively low value, the starting torque increases until it becomes maximum when $R_2 = X_2$. If the rotor resistance is increased beyond this optimum value, the starting torque will decrease.

Performance Characteristics of Three phase Induction Motor

The equivalent circuits derived in the preceding section can be used to predict the performance characteristics of the induction machine. The important performance characteristics in the steady state are the efficiency, power factor, current, starting torque, maximum (or pull-out) torque.

The complete torque-speed characteristic

In order to estimate the speed torque characteristic let us suppose that a sinusoidal voltage is impressed on the machine. Recalling that the equivalent circuit is the per-phase representation of the machine, the current drawn by the circuit is given by

$$I_s = \frac{V_s}{(R_s + \frac{R'_r}{s}) + j(X_{ls} + X'_{lr})}$$

Where, Vs is the phase voltage phasor and Is is the current phasor. The magnetizing current is neglected. Since this current is flowing through R′r/s, the air-gap power is given by

$$\begin{aligned} P_g &= |I_s|^2 \frac{R'_r}{s} \\ &= \frac{V_s}{(R_s + \frac{R'_r}{s})^2 + (X_{ls} + X'_{lr})^2} \frac{R'_r}{s} \end{aligned}$$

The mechanical power output was shown to be ω_m (1−s)Pg (power dissipated in R′r/s). The torque is obtained by dividing this by the shaft speed .Thus we have,

$$\frac{P_g(1-s)}{\omega_m} = \frac{P_g(1-s)}{\omega_s(1-s)} = |I_s|^2 \frac{R'_r}{s\omega_s}$$

where ω_m is the synchronous speed in radians per second and s is the slip. Further, this is the torque produced per phase. Hence the overall torque is given by

$$T_e = \frac{3}{\omega_s} . \frac{V_s^2}{(R_s + \frac{R'_r}{s})^2 + (X_{ls} + X'_{lr})} . \frac{R'_r}{s}$$

The torque may be plotted as a function of ‘s’ and is called the torque-slip (or torque- speed, since slip indicates speed) characteristic a very important characteristic of the induction machine.

A typical torque-speed characteristic is shown in Fig: 3.18. This plot corresponds to a 3 kW, 4 pole, and 60 Hz machine. The rated operating speed is 1780 rpm.

Further, this curve is obtained by varying slip with the applied voltage being held constant. Coupled with the fact that this is an equivalent circuit valid under steady state, it implies that if this characteristic is to be measured experimentally, we need to look at the torque for a given speed after all transients have died down. One cannot, for example, try to obtain this curve by directly starting the motor with full voltage applied to the terminals and measuring the torque and speed dynamically as it runs up to steady speed.

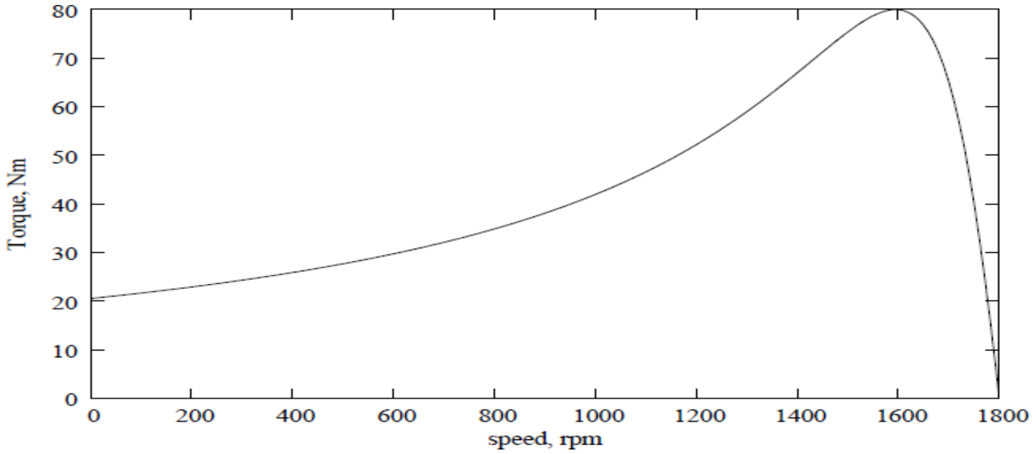
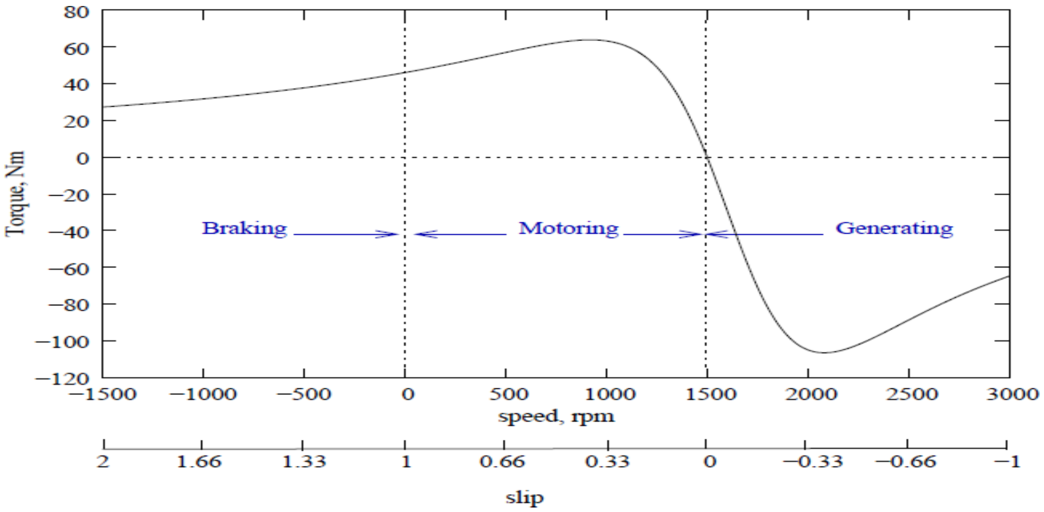


Fig: 2.18

With respect to the direction of rotation of the air-gap flux, the rotor maybe driven to higher speeds by a prime mover or may also be rotated in the reverse direction. The torque-speed relation for the machine under the entire speed range is called the complete speed-torque characteristic. A typical curve is shown in Fig: 3.19 for a four-pole machine, the synchronous speed being 1500 rpm. Note that negative speeds correspond to slip values greater than 1, and speeds greater than 1500 rpm correspond to negative slip. The plot also shows the operating modes of the induction machine in various regions.



The slip axis is

Fig: 2.19

also shown for convenience.

Effect of Rotor Resistance on Speed Torque Characteristic

Restricting ourselves to positive values of slip, we see that the curve has a peak point. This is the maximum torque that the machine can produce, and is called as stalling torque. If the load torque is more than this value, the machine stops rotating or stalls. It occurs at a slip ˆs, which for the machine of Fig: 3.19 is 0.38. At values of slip lower than ˆs, the curve falls steeply down to zero at s = 0. The torque at synchronous speed is therefore zero. At values of slip higher than s = ˆs, the curve falls slowly to a minimum value at s = 1. The torque at s = 1 (speed = 0) is called the starting torque. The value of the stalling torque may be obtained by differentiating the expression for torque with respect to zero and setting it to zero to find the value of ˆs. Using this method, we can write

$$\hat{s} = \frac{\pm R_r'}{\sqrt{R_r'^2 + (X_{ls} + X_{lr}')^2}}$$

Substituting ˆs into the expression for torque gives us the value of the stalling torque ˆ Te,

$$\hat{T}_e = \frac{3V_s^2}{2\omega_s}.\frac{1}{R_s \pm \sqrt{R_s^2 + (X_{ls} + X_{lr}')^2}}$$

The negative sign being valid for negative slip.

The expression shows that ˆ Te is the independent of R′r, while ˆs is directly proportional to R′r. This fact can be made use of conveniently to alter ˆs. If it is possible to change R′r, then we can get a whole series of torque-speed characteristics, the maximum torque remaining constant all the while.

We may note that if R′r is chosen equal to =

$$\sqrt{R_s^2 + (X_{ls} + X_{lr}')^2}$$

The ˆs, becomes unity, which means that the maximum torque occurs at starting. Thus changing of R′r, wherever possible can serve as a means to control the starting torque Fig: 3.20.

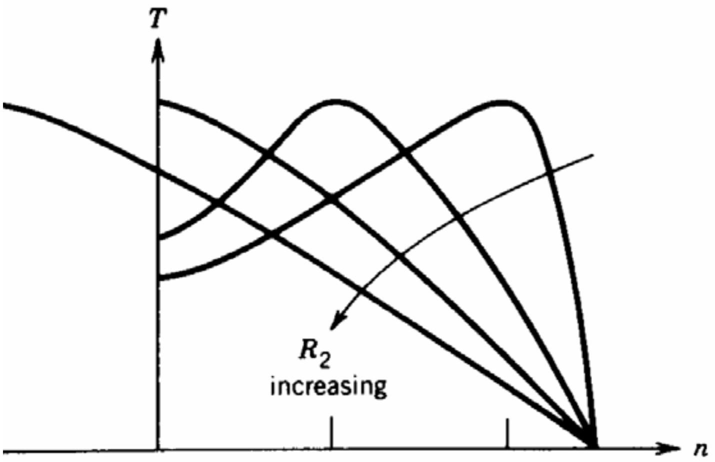


Fig: 2.20

While considering the negative slip range, (generator mode) we note that the maximum torque is higher than in the positive slip region (motoring mode).

Operating Point and Stable & Unstable region of Operation

Consider a speed torque characteristic shown in fig 2.21 for an induction machine, having the load characteristic also superimposed on it. The load is a constant torque load i.e. the torque required for operation is fixed irrespective of speed.

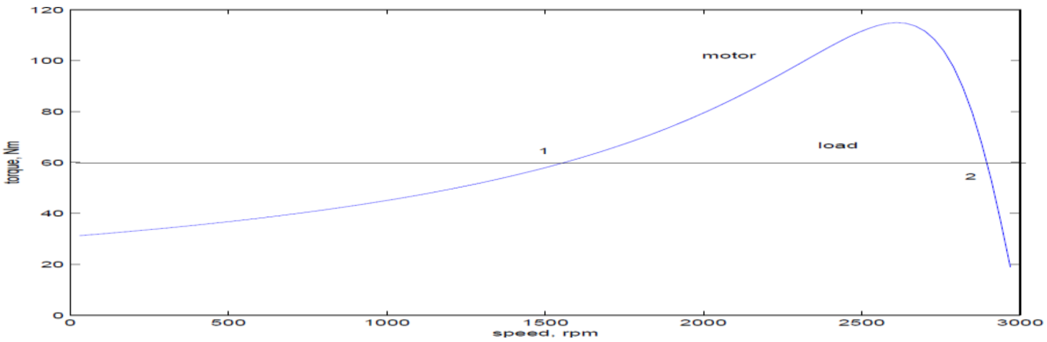


Fig: 2.21

The system consisting of the motor and load will operate at a point where the two characteristics meet. From the above plot, we note that there are two such points. We therefore need to find out which of these is the actual operating point. To answer this we must note that, in practice, the characteristics are never fixed; they change slightly with time. It would be appropriate to consider a small band around the curve drawn where the actual points of the characteristic will lie. This being the case let us considers that the system is operating at point 1, and the load torque demand increases slightly. This is shown in Fig: 2.21, where the change is exaggerated for clarity. This would shift the point of operation to a point 1′ at which the slip would be less and the developed torque higher.

The difference in torque developed ∆Te, being positive will accelerate the machine. Any overshoot in speed as it approaches the point 1′ will cause it to further accelerate since the developed torque is increasing. Similar arguments may be used to show that if for some reason the developed torque becomes smaller the speed would drop and the effect is cumulative. Therefore we may conclude that 1 is not a stable operating point.

Let us consider the point 2. If this point shifts to 2′, the slip is now higher (speed is lower) and the positive difference in torque will accelerate the machine. This behavior will tend to bring the operating point towards 2 once again. In other words, disturbances at point 2 will not cause a runaway effect. Similar arguments may be given for the case where the load characteristic shifts down. Therefore we conclude that point 2 is a stable operating point.

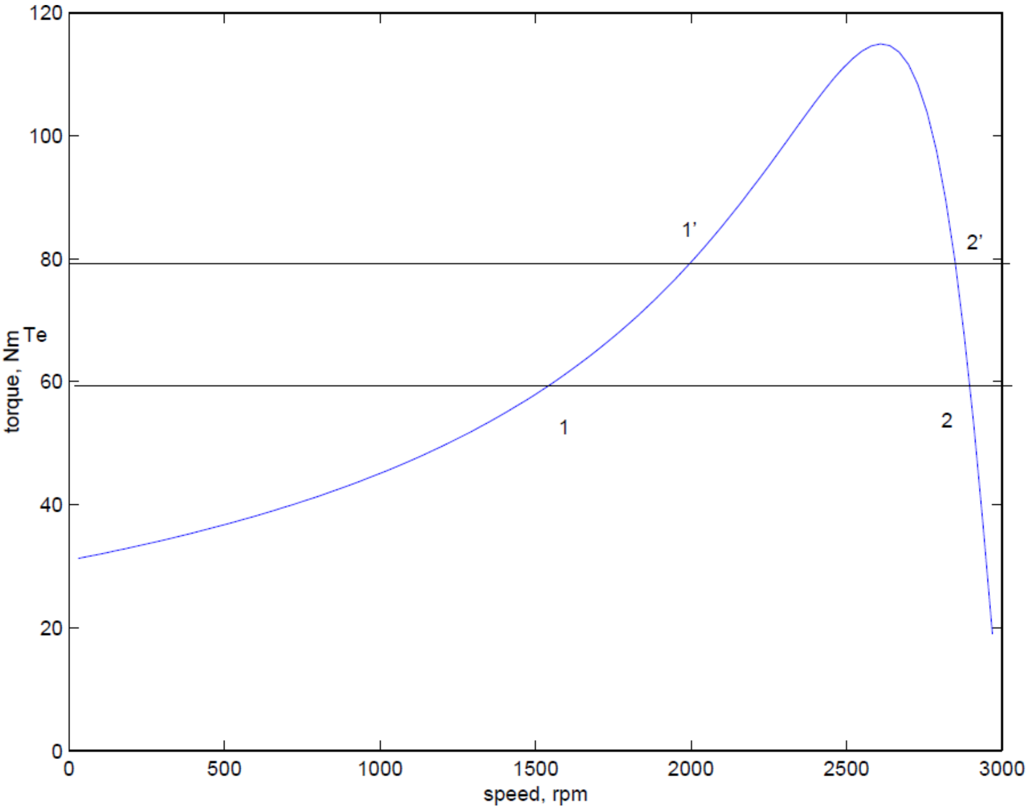


Fig: 2.22

From the above discussions, we can say that the entire region of the speed-torque characteristic from s = 0 to s = ˆs is an unstable region, while the region from s = ˆs to s = 0 is a stable region. Therefore the machine will always operate between s = 0 and s = ˆs.

Circle diagram

To analyse the three phase induction motor performance using circle diagram we need to determine the equivalent circuit parameters of the machine.

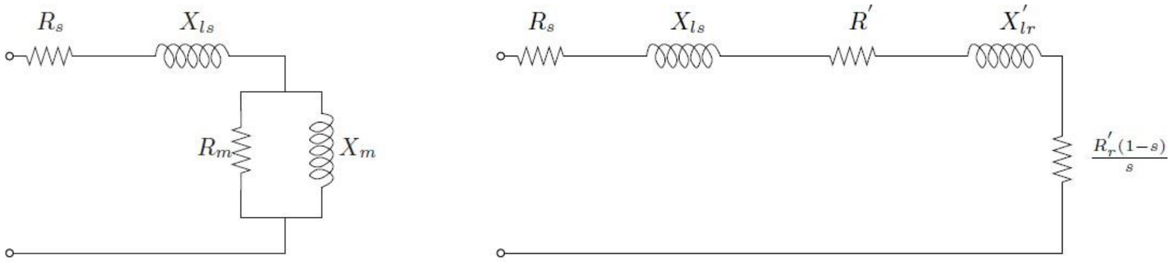
Tests to Determine the Equivalent Circuit Parameters

In order to find values for the various elements of the equivalent circuit, tests must be conducted on a particular machine, which is to be represented by the equivalent circuit. In order to do this, we note the following.

When the machine is run on no-load, there is very little torque developed by it. In an ideal case where there is no mechanical losses, there is no mechanical power developed at no-load. Recalling the explanations in the section on torque production, the flow of current in the rotor is indicative of the torque that is produced. If no torque is produced, one may conclude that no current would be flowing in the rotor either. The rotor branch acts like an open circuit. This conclusion may also be reached by reasoning that when there is no load, an ideal machine will run up to its synchronous speed where the slip is zero resulting in an infinite impedance in the rotor branch.

When the machine is prevented from rotation, and supply is given, the slip remains at unity. The elements representing the magnetizing branch Rm & Xm are high impedances much larger than R_r' & X_{lr}' in series. Thus, in the exact equivalent circuit of the induction machine, the magnetizing branch may be neglected.

From these considerations, we may reduce the induction machine equivalent circuit of Fig.3.13 & Fig: 2.15 to those shown in Fig: 2.16.



(a) No-load equivalent (b) Blocked rotor equivalent

Fig: 2.16

These two observations and the reduced equivalent circuits are used as the basis for the two most commonly used tests to find out the equivalent circuit parameters — the blocked rotor test and no load test. They are also referred to as the short circuit test and open circuit test respectively in conceptual analogy to the transformer.

No-load test

The behavior of the machine may be judged from the equivalent circuit of Fig: 2.16 (a). The current drawn by the machine causes a stator-impedance drop and the balance voltage is applied across the magnetizing branch. However, since the magnetizing branch impedance is large, the current drawn is small and hence the stator impedance drop is small compared to the applied voltage (rated value). This drop and the power dissipated in the stator resistance are therefore neglected and the total power drawn is assumed to be consumed entirely as core loss. This can also be seen from the approximate equivalent circuit, the use of which is justified by the foregoing arguments. This test therefore enables us to compute the resistance and inductance of the magnetizing branch in the following manner.

Let applied voltage = V_s. Then current drawn is given by

$$I_s = \frac{V_s}{R_m} + \frac{V_s}{jX_m}$$

The power drawn is given by

$$P_s = \frac{V_s^2}{R_m} \Rightarrow R_m = \frac{V_s^2}{P_s}$$

Vs, Is and Ps are measured with appropriate meters. With Rm known by above equation, Xm also can be found. The current drawn is at low power factor and hence a suitable wattmeter should be used.

Blocked-rotor Test

In this test the rotor is prevented from rotation by mechanical means and hence the name. Since there is no rotation, slip of operation is unity, S = 1. The equivalent circuit valid under these conditions is shown in Fig: 2.16 (b). Since the current drawn is decided by the resistance and leakage impedances alone, the magnitude can be very high when rated voltage is applied. Therefore in this test, only small voltages are applied — just enough to cause rated current to flow. While the current magnitude depends on the resistance and the reactance, the power drawn depends on the resistances. The parameters may then be determined as follows. The source current and power drawn may be written as -

$$\begin{aligned} I_s &= \frac{V_s}{(R_s + R_r') + j(X_s + X_r')} \\ P_s &= |I_s|^2 (R_s + R_r') \end{aligned}$$

In the test Vs, Is and Ps are measured with appropriate meters. Above equation enables us to compute (Rs + R′r). Once this is known, (Xs + X′r) may be computed from the above equation.

Note that this test only enables us to determine the series combination of the resistance and the reactance only and not the individual values. Generally, the individual values are assumed to be equal; the assumption Rs = R′r, and Xs = X′r suffices for most purposes.

In practice, there are differences. If more accurate estimates are required IEEE guidelines may be followed which depend on the size of the machine.

These two tests determine the equivalent circuit parameters in a ‘Stator-referred’ sense, i.e., the rotor resistance and leakage inductance are not the actual values but what they ’appear to be’ when looked at from the stator. This is sufficient for most purposes as interconnections to the external world are generally done at the stator terminals. $I_2 s X_2$

Percent Voltage Unbalance =100 * (Maximum Voltage Deviation/ Average Voltage)

What is a Circle Diagram

A circle diagram is a graphical representation of the performance of an electrical machine. It is commonly used to illustrate the performance of transformers, alternators, synchronous motors, and induction motors. It is very useful to study the performance of an electric machine under a large variety of operating conditions. The diagrammatic representation of a circle diagram makes it much easier to understand and remember compared to theoretical and mathematical descriptions.

Importance of Circle Diagram

The diagram provides information which is not provided by an ordinary phasor diagram. A phasor diagram gives relation between current and voltage only at a single circuit condition. If the condition changes, we need to draw the phasor diagram again. But a circle diagram may be referred to as a phasor diagram drawn in one plane for more than one circuit conditions. On the context of induction motor, which is our main interest, we can get information about its power output, power factor, torque, slip, speed, copper loss, efficiency etc. in a graphical or in a diagrammatic representation.

Test Performed to Compute Data Required for Drawing Circle Diagram

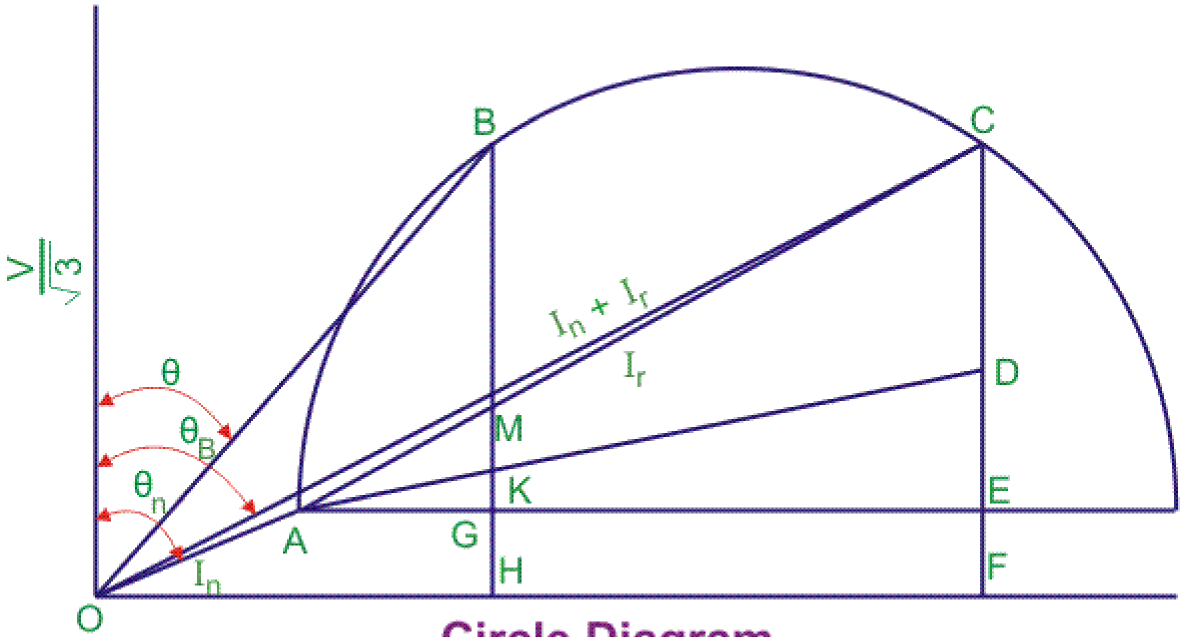
We have to perform no load and blocked rotor test in an induction motor.

In no load test, the induction motor is run at no load and by two watt meter method, its total power consumed is calculated which is composed of no load losses only. Slip is assumed to be zero. From here no load current and the angle between voltage and current required for drawing circle diagram is calculated. The angle will be large as in the no load condition induction motor has high inductive reactance.

In block rotor test, rotor is blocked which is analogous to short circuiting secondary of a transformer. From this test, we need to calculate short circuit current and the lag angle between voltage and current for drawing circle diagram. Also, we need rotor and stator copper loss.

How to Draw Circle Diagram of Induction Motor

A circle diagram is commonly used to represent an induction motor. To draw a circle diagram like the one below:



Circle Diagram

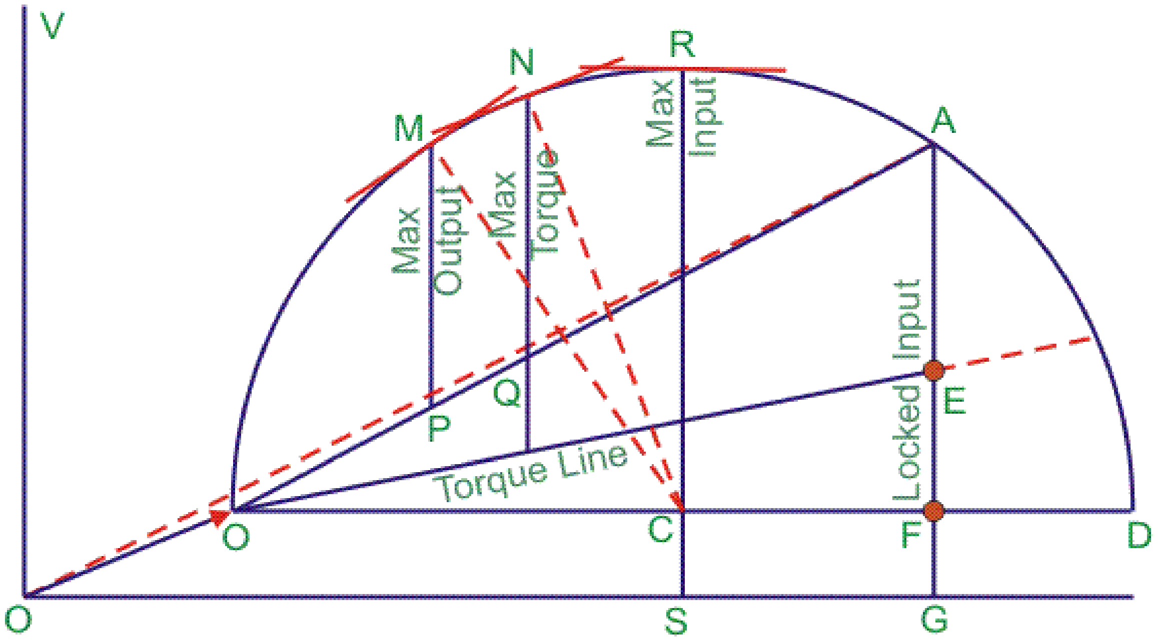
1) The no-load current and the no load angle calculated from no load test is plotted. This is shown by the line OA, where Θ0 is the no load power factor angle.

2) The short circuit current and the angle obtained from block rotor test is plotted. This is shown by the line OC and the angle is shown by ϴB.
3) The right bisector of the line AC is drawn which bisects the line and it is extended to cut in the line AE which gives us the centre.
4) The stator current is calculated from the equivalent circuit of the induction motor which we get from the two tests. That current is plotted in the circle diagram according to the scale with touching origin and a point in the circle diagram which is shown by B.
5) The line AC is called the power line. By using the scale for power conversion that we have taken in the circle diagram, we can get the output power if we move vertically above the line AC to the periphery of the circle. The output power is given by the line MB.
6) The total copper loss is given by the line GM.
7) For drawing the torque line, the total copper loss should be separated to both the rotor copper loss and stator copper loss. The line DE gives the stator copper loss and the line CD gives the rotor copper loss. In this way, the point E is selected.
8) The line AD is known as torque line which gives the torque developed by induction motor.

Parts of a Circle Diagram

The parts of a circle diagram include:

a) Maximum output power
b) Maximum torque
c) Maximum Input Power



Maximum output power

When the tangent to the circle is parallel to the line then output power will be maximum. That point M is obtained by drawing a perpendicular line from the center to the output line and extending it to cut at M.

Maximum torque

When the tangent to the circle is parallel to the torque line, it gives maximum torque. This is obtained by drawing a line from the center in perpendicular to the torque line AD and extending it to cut at the circle. That point is marked as N.

Maximum Input Power

It occurs when tangent to the circle is perpendicular to the horizontal line. The point is the highest point in the circle diagram and drawn to the center and extends up to S. That point is marked as R.

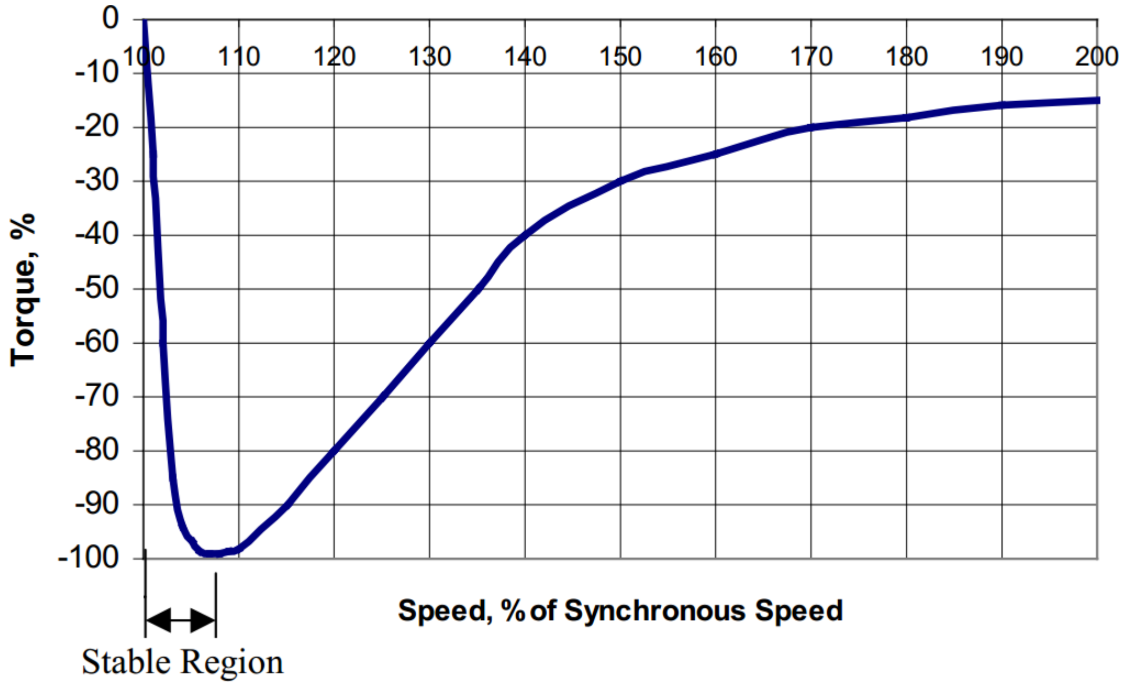
Conclusion of Circle Diagram

This method is based on some approximations that we have used in order to draw the circle diagram and also, there is some rounding off of the values as well. So although there is some error to this method, it can still give us a good approximation of the results. The main downside to a circle diagram is that although it is easy to interpret and read, it can be quite time consuming to draw. Alternative methods include using mathematical formulas or equivalent circuit models instead to find out the various performance parameters. If you’re looking to learn more about circle diagrams and other electrical engineering topics, check out our full list of basic electrical questions.

Induction Generator

When a squirrel cage induction motor is energized from a three phase power system and is mechanically driven above its synchronous speed it will deliver power to the system. An induction generator receives its excitation (magnetizing current) from the system to which it is connected. It consumes rather than supplies reactive power (KVAR) and supplies only real power (KW) to the system. The KVAR required by the induction generator plus the KVAR requirements of all other loads on the system must be supplied from synchronous generators or static capacitors on the system.

Operating as a generator at a given percentage slip above synchronous speed, the torque, current, efficiency and power factor will not differ greatly from that when operating as a motor. The same slip below synchronous speed, the shaft torque and electric power flow is reversed. Typical speed torque characteristic of induction generator is shown in Fig: 2.41.



Now for example, a 3600 RPM squirrel cage induction motor which delivers full load output at 3550 RPM as a motor will deliver full rated power as a generator at 3650 RPM. If the half-load motor speed is 3570 RPM, the output as a generator will be one-half of rated value when driven at 3630 RPM, etc. Since the induction generator is actually an induction motor being driven by a prime mover.

Advantages.

1) It is less expensive and more readily available than a synchronous generator.
2) It does not require a DC field excitation voltage.
3) It automatically synchronizes with the power system, so its controls are simpler and less expensive.

Disadvantages

1) It is not suitable for separate, isolated operation
2) It consumes rather than supplies magnetizing KVAR
3) It cannot contribute to the maintenance of system voltage levels (this is left entirely to the synchronous generators or capacitors)
4) In general it has a lower efficiency.
5)

Induction generator application.

As energy costs so high, energy recovery became an important part of the economics of most industrial processes. The induction generator is ideal for such applications because it requires very little in the way of control system or maintenance.

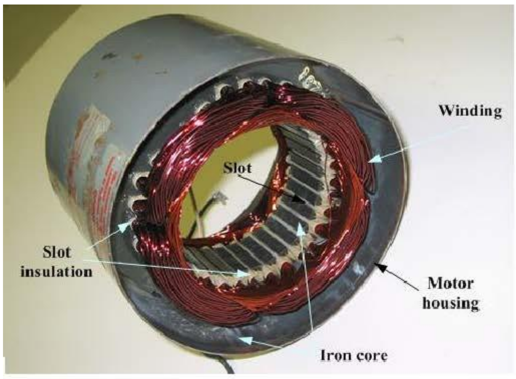
Because of their simplicity and small size per kilowatt of output power, induction generators are also favored very strongly for small windmills. Many commercial windmills are designed to operate in parallel with large power systems, supplying a fraction of the customer’s total power needs. In such operation, the power system can be relied on for voltage & frequency control, and static capacitors can be used for power-factor correction.

MODULE-III

SINGLE PHASE INDUCTION MOTORS

Single Phase Induction Motors

Single phase Induction motors perform a great variety of useful services at home, office, farm, factory and in business establishments. Single phase motors are generally manufactured in fractional HP ratings below 1 HP for economic reasons. Hence, those motors are generally referred to as fractional horsepower motors with a rating of less than 1 HP. Most single phase motors fall into this category. Single phase Induction motors are also manufactured in the range of 1.5, 2, 3 and up to 10 HP as a special requirement.



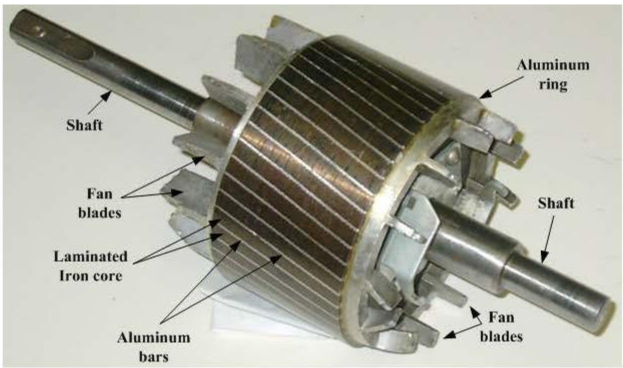


Fig: 3.1(a) Stator

Fig: 3.1(b) Squirrel cage rotor

Theory of Operation

A single phase induction motor is similar in construction to that of a poly phase induction motor with difference that its stator has only one winding. If such a stator is supplied with single phase alternating current, the field produced by it changes in magnitude and direction sinusoidal. Thus the magnetic field produced in the air gap is alternating one but not rotating as a result these kind of motors are NOT SELF STARTING. Fig: 3.2 (a) shows the torque-speed characteristic of single phase induction motor.

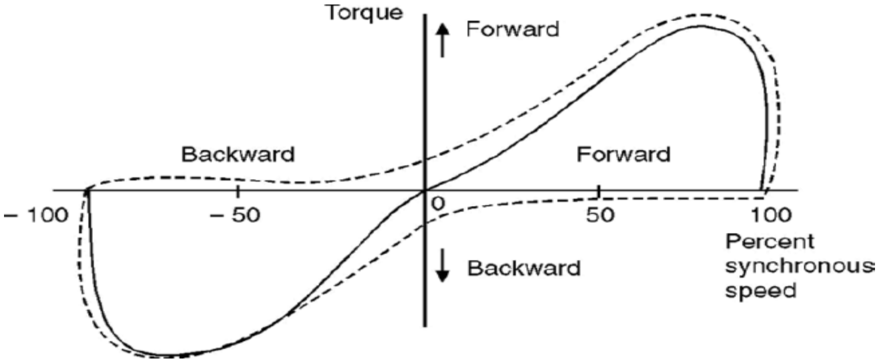


Fig: 3.2 (a)

Such an alternating filed is equivalent to two fields of equal magnitude rotating in opposite directions at equal speed as explained below:

Double Revolving Field Theory of Single Phase Induction Motor

Consider two magnetic fields represented by quantities OA and OB of equal magnitude revolving in opposite directions as shown in fig: 3.1.

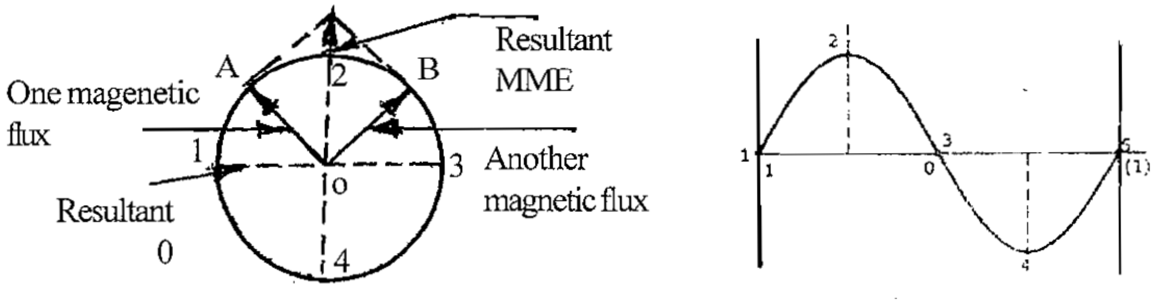


Fig: 3.2 (b)

The resultant of the two fields of equal magnitude rotating in opposite directions is alternating. Therefore an alternating current can be considered as having two components which are of equal in magnitude and rotating in opposite directions.

From the above, it is clear that when a single phase alternating current is supplied to the stator of a single phase motor, the field produced will be of alternating in nature which can be divided into two components of equal magnitude one revolving in clockwise and other in counter clockwise direction.

If a stationary squirrel cage rotor is kept in such a field equal forces in opposite direction will act and the rotor will simply vibrate and there will be no rotation.

But if the rotor is given a small jerk in any direction in this condition, it will go on revolving and will develop torque in that particular direction. It is clear from the above that a single phase induction motor when having only one winding is not a self-starting. To make it a self-starting anyone of the following can be adopted.

1) Split phase starting.
2) Repulsion starting.
3) Shaded pole starting.

Methods of Starting

It is clear from previous discussion that a single phase induction motor when having only one winding and it is not self-starting. To make it a self-starting anyone of the following can be adopted.

1) Split phase starting.
2) Repulsion starting.
3) Shaded pole starting.

1) Principle of split phase induction motor

The basic principle of operation of a split phase induction motor is similar to that of a poly phase induction motor. The main difference is that the single phase motor does not produce a rotating magnetic field but produces only a pulsating filed.

Hence, to produce the rotating magnetic field for self-starting, phase splitting is to be done to make the motor to work as a two phase motor for starting.

Working of Split Phase Motor

In split phase motor two windings named as main winding and starting winding are provided. At the time of starting, both the main and starting windings should be connected across the supply to produce the rotating magnetic field.

The rotor is of a squirrel cage type and the revolving magnetic field sweeps part the stationary rotor, inducing emf in the rotor. As the rotor bars are short-circuited, a current flows through them producing a magnetic field.

This magnetic field opposes the revolving magnetic field and will combine with the main filed to produce a revolving filed. By this action, the rotor starts revolving in the same direction of the rotating magnetic field as in the case of a squirrel cage induction motor.

Hence, once the rotor starts rotating, the starting winding can be disconnected from the supply by some mechanical means as the rotor and stator fields from a revolving magnetic field. There are several types of split phase motors.

Types of split-phase induction motors

a) Resistance-start, induction-run motors
b) Capacitor-start, induction-run motors
c) Capacitor-start, capacitor-run motors
d) Shaded pole motors.

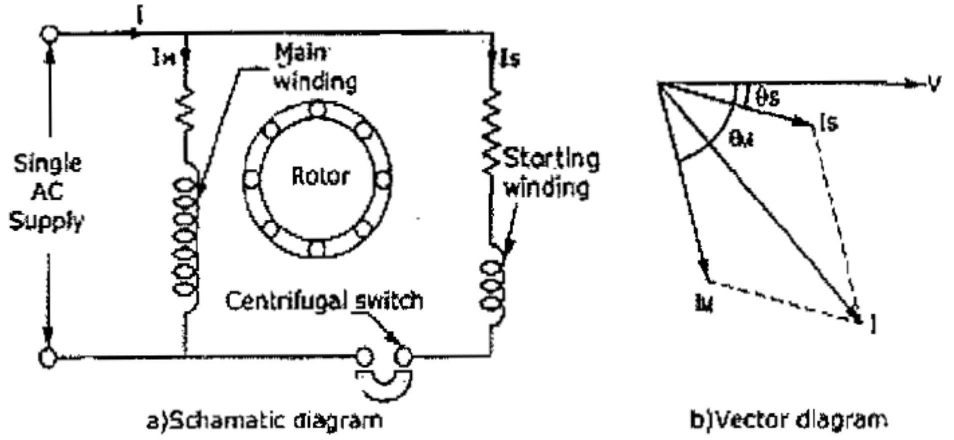
a) Resistance-start, induction-run motors

As the starting torque of this type of motor is relatively small and its starting current is high, these motors are most commonly used for rating up to 0.5 HP where the load could be started easily. The essential parts are shown in Fig: 3.7.

i) Main winding or running winding.
ii) Auxiliary winding or starting winding
iii) Squirrel cage type rotor.
iv) Centrifugal switch.

Construction and working

The starting winding is designed to have a higher resistance and lower reactance than the main winding. This is achieved by using small conductors in the auxiliary winding than in the main winding. The main winding will have higher inductance when surrounded by more iron, which could be made possible by placing it deeper into the stator slots, it is obvious that the current would split as shown in Fig: 3.7(b).



a)Schamatic diagram

b)Vector diagram

Fig: 3.7

The starting current "I" start will lag the main supply voltage "V" line by 15 degree and the main winding current. "I" main lags the main voltage by about 80 degree. Therefore, these currents will differ in time phase and their magnetic fields will combine to produce a rotating magnetic field. When the motor has come up to about 75 to 80% of synchronous speed, the starting winding is opened by a centrifugal switch and the motor will continue to operate as a single phase motor.

Characteristics:

At the point where the starting winding is disconnected, the motor develops nearly as much torque with the main winding alone as with both windings connected. This can be observed from, the typical torque-speed characteristics of this motor, as shown in Fig: 4.8.

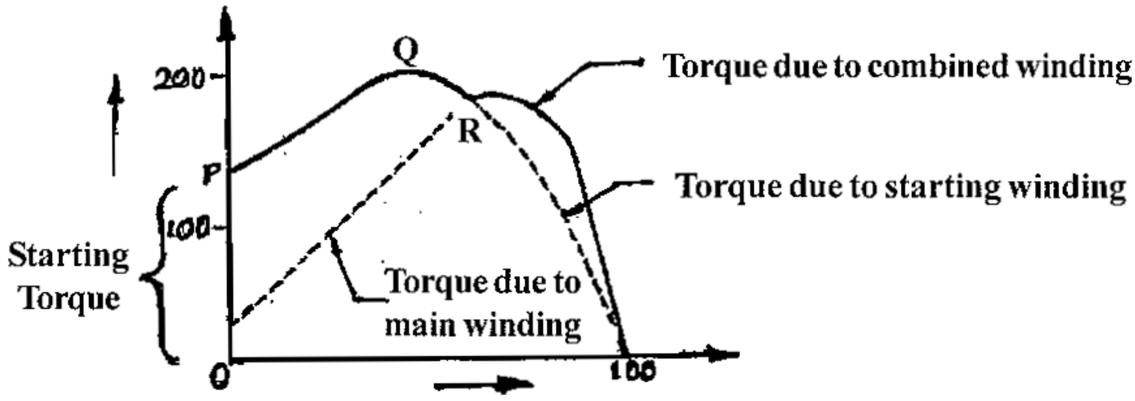


Fig: 4.8

The direction of rotating of a split-phase motor is determined by the way the main and auxiliary windings are connected. Hence, either by changing the main winding terminals or by changing the starting winding terminals, the reversal of direction of rotating could be obtained.

Applications

These motors are used for driving fans, grinders, washing machines.

b) Capacitor-start, induction-run motor

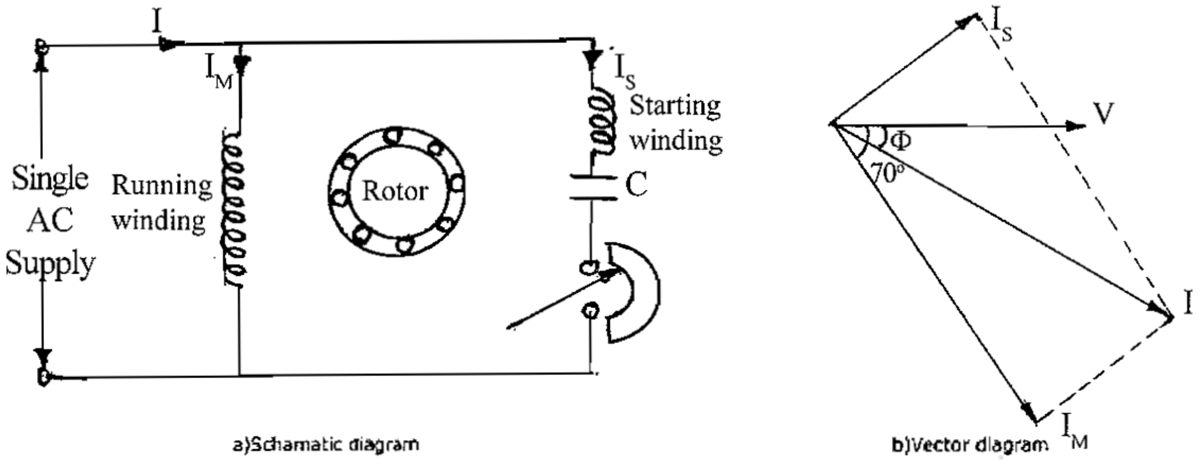
A drive which requires a large starting torque may be fitted with a capacitor-start, induction- run motor as it has excellence starting torque as compared to the resistance-start, induction-run motor.

Construction and working

Fig: 4.9(a) shows the schematic diagram of a capacitor-start, induction-run motor. As shown, the main winding is directly connected across the main supply whereas the starting winding is connected across the main supply through a capacitor and centrifugal switch. Both these windings are placed in a stator slot at 90 degree electrical apart, and a squirrel cage type rotor is used. As shown in Fig: 4.9(b), at the time of starting the current in the main winding lags the supply voltages by 90 degrees, depending upon its inductance and resistance. On the other hand, the current in the starting winding due to its capacitor will lead the applied voltage, by say 20 degrees.

Hence, the phase difference between the main and starting winding becomes near to 90 degrees. This in turn makes the line current to be more or less in phase with its applied voltage, making the power factor to be high, thereby creating an excellent starting torque.

However, after attaining 75% of the rated speed, the centrifugal switch operates opening the starting winding and the motor then operates as an induction motor, with only the main winding connected to the supply.



a)Schamatic diagram   b)Vector diagram

Fig: 4.9

As shown in Fig: 4.9(b), the displacement of current in the main and starting winding is about 80/90 degrees, and the power factor angle between the applied voltage and line current is very small. This results in producing a high power factor and an excellent starting torque, several times higher than the normal running torque as shown in Fig: 4.10.

Characteristics:

The torque-speed characteristics of this motor is shown in Fig: 4.10.

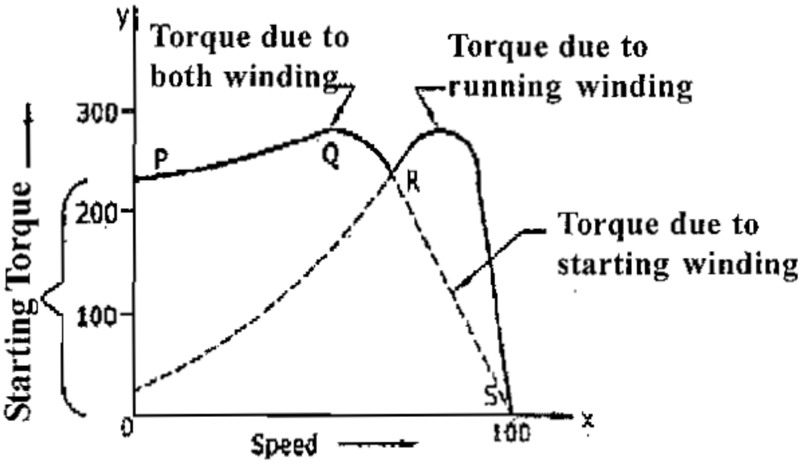


Fig: 4.10

In order to reverse the direction of rotation of the capacitor-start, induction-run motor, either the starting or the main winding terminals should be changed. This is due to the fact that the direction of rotation depends upon the instantaneous polarities of the main field flux and the flux produced by the starting winding. Therefore, reversing the polarity of one of the field will reverse the torque.

Applications

Due to the excellent starting torque and easy direction-reversal characteristics,

- i) Used in belted fans,
- ii) Used in blowers dryers,
- iii) Used in washing machines,
- iv) Used in pumps and compressors.

c) Capacitor-start, capacitor-run motors

As discussed earlier, one capacitor-start, induction-run motors have excellent starting torque, say about 300% of the full load torque and their power factor during starting in high.

However, their running torque is not good, and their power factor, while running is low. They also have lesser efficiency and cannot take overloads.

Construction and working

The aforementioned problems are eliminated by the use of a two valve capacitor motor in which one large capacitor of electrolytic (short duty) type is used for starting whereas a smaller capacitor of oil filled (continuous duty) type is used for running, by connecting them with the starting winding as shown in Fig:4.11. A general view of such a two valve capacitor motor is shown in Fig: 4.11.

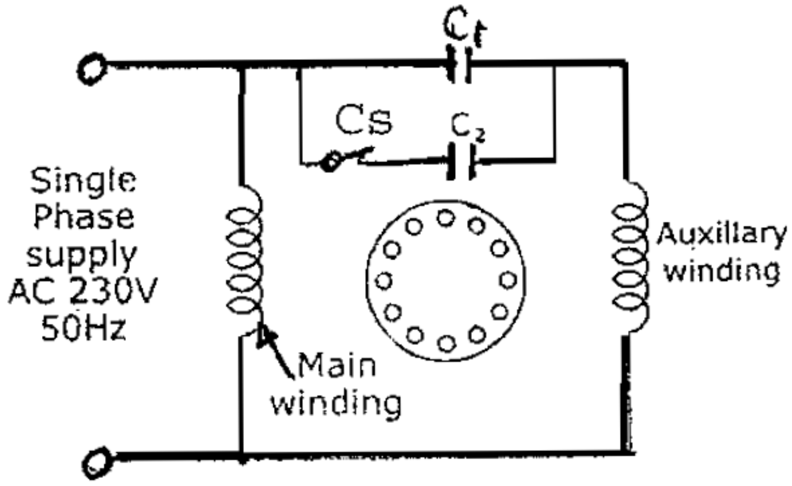


Fig: 4.11

This motor also works in the same way as a capacitor-start, induction-run motor, with exception, that the capacitor C1 is always in the circuit, altering the running performance to a great extent. The starting capacitor which is of short duty rating will be disconnected from the starting winding with the help of a centrifugal switch, when the starting speed attains about 75% of the rated speed.

Characteristics

The torque-speed characteristics of this motor is shown in Fig: 4.12.

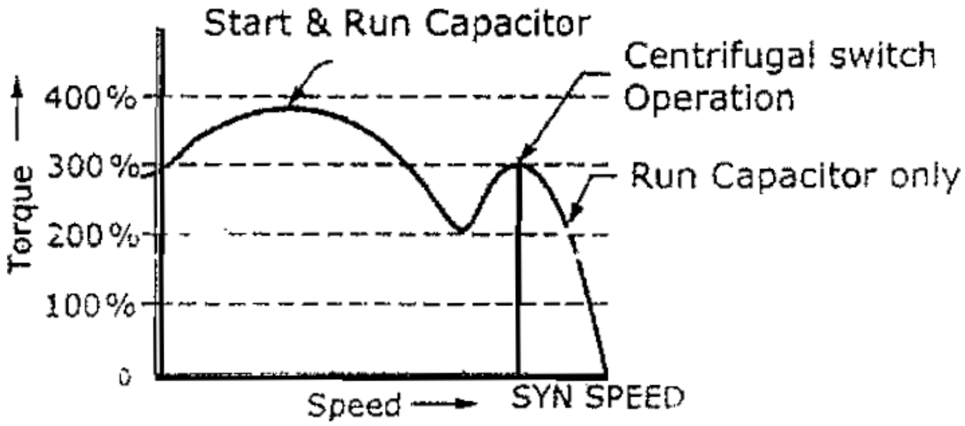


Fig: 4.12

This motor has the following advantages:

i) The starting torque is 300% of the full load torque
ii) The starting current is low, say 2 to 3 times of the running current.
iii) Starting and running power factor are good.
iv) Highly efficient running.
v) Extremely noiseless operation.
vi) Can be loaded upto 125% of the full load capacity.

Applications:

Used for compressors, refrigerators, air-conditioners, etc.

Higher starting torque.

High efficiency, higher power factor and overloading.

Costlier than the capacitor-start — Induction run motors of the same capacity.

Equivalent circuit of single phase induction motor

The equivalent circuit of single phase induction motor is shown below (Fig: 4.3)

Determination of Equivalent Circuit Parameters of Single Phase Induction motor

It is possible to find the parameters of the equivalent circuit of the single phase induction motor experimentally as shown in Fig.4.4. For this purpose, three tests should be conducted:

The DC Test:

$$R_{DC} = \frac{V_{DC}}{I_{DC}}$$

The DC resistance of the stator can be measured by applying DC current to the terminals of the main winding and taking the reading of the voltage and the current (or using ohmmeter) and determine the DC resistance as follows:

Then, the AC resistance is given by:

$$R_{AC} = 1.25\ R_{DC}$$

The blocked rotor test:

When the rotor is locked (i.e. prevented from running), $S_b = S_f = 1$. The secondary impedances become much less than the magnetizing branches and the corresponding equivalent circuit becomes that of Fig: 4.5.

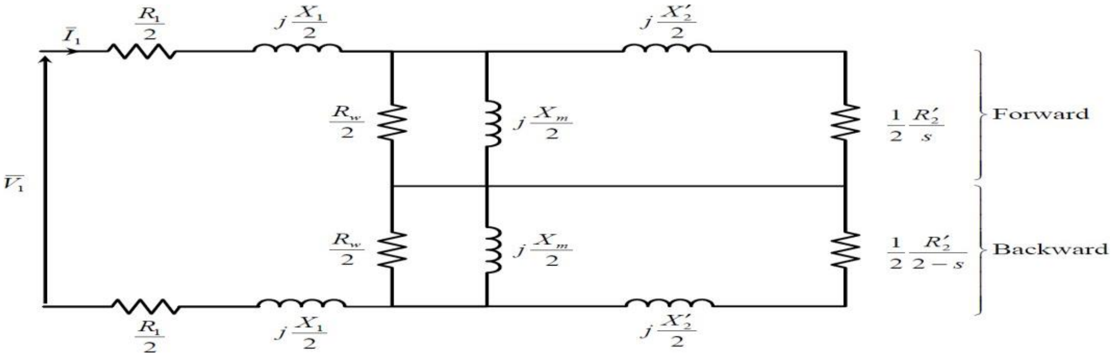


Fig: 4.4 Equivalent circuit of single phase induction motor.

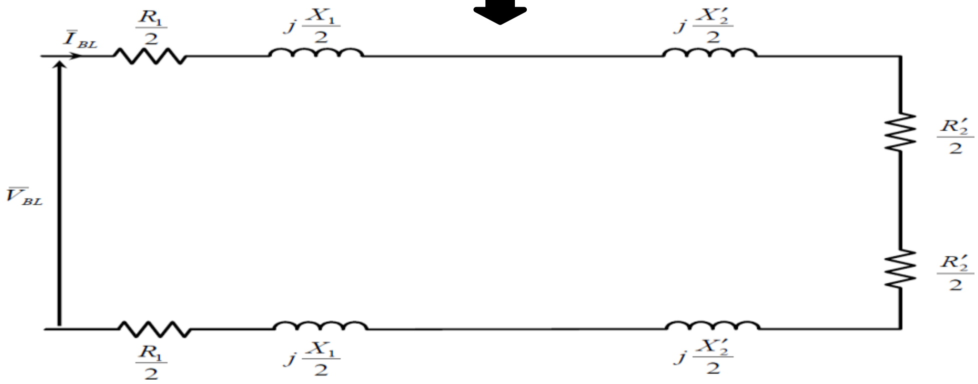


Fig: 4.5(a) Approximate equivalent circuit of the single phase induction motor at standstill.

The circuit in Fig: 4.5 (a) can be rearranged to the equivalent circuit that is shown in Fig: 4.5(b).

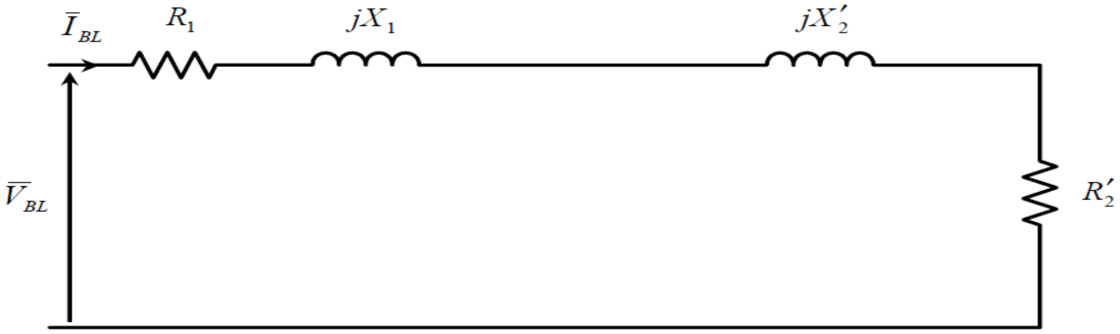


Fig: 4.5(b) Rearranged approximate equivalent circuit of the single phase induction motor at standstill.

The readings to be obtained from this test are:

a) Single phase power P_{BL}
b) Phase voltage V_{BL}
c) Phase current I_{BL}

Then, R_{eq}, Z_{eq}, and X_{eq} can be obtained using the following equations:

$$R_{eq} = \frac{P_{BL}}{I_{BL}^2}$$

$$Z_{eq} = \frac{V_{BL}}{I_{BL}}$$

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$$

Separation of X_1, X'_2, R_1, and R'_2 can be done as follows:

$$X_1 = X'_2 = \frac{1}{2} X_{eq}$$

$$R'_2 = R_{eq} - R_1$$

The no load test:

When the induction motor is allowed to run freely at no load, the forward slip Sf approaches zero and the backward slip Sb approaches 2 (Sf = s, Sb = 2-s). The secondary forward impedance becomes very large with respect to the magnetizing branch, while the secondary backward impedance becomes very small if compared with the magnetizing branch. Accordingly, the equivalent circuit corresponding to these operating conditions can be approximated by that of Fig: 4.6.

The readings to be obtained from this test are:

d) Single phase power P_{NL}

e) Phase voltage V_{NL}

f) Phase current I_{NL}

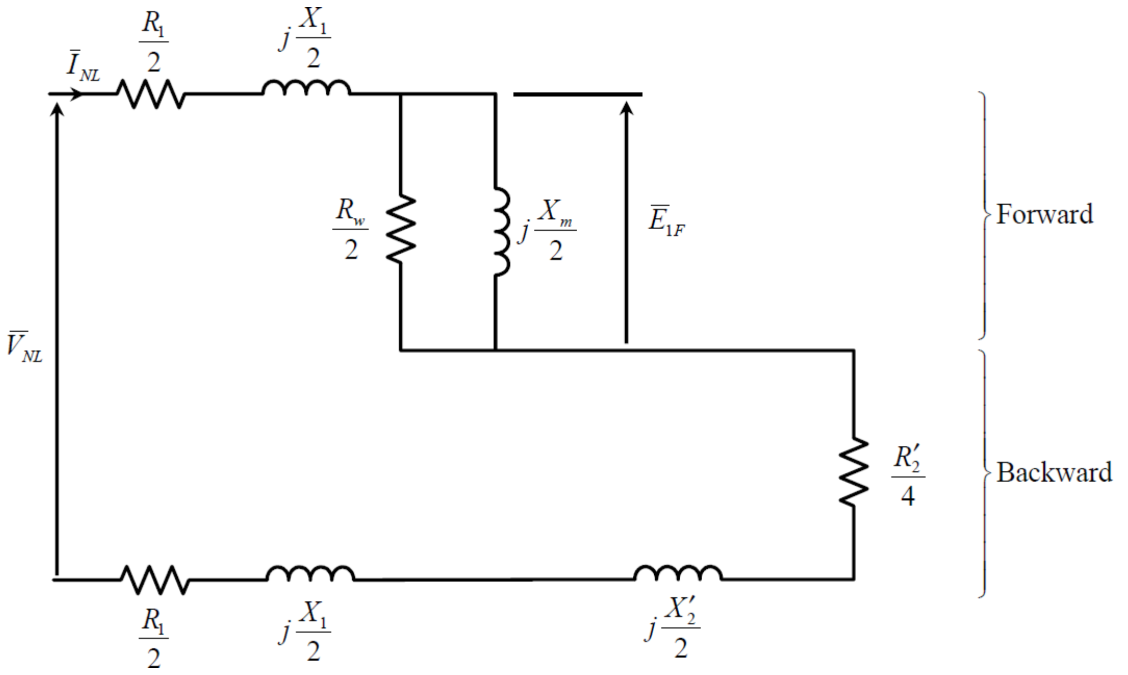


Fig: 4.6 (a) Approximate equivalent circuit of the single phase induction motor at no load.

⬇

The circuit in Fig: 4.6 (a) can be rearranged to the equivalent circuit that is shown in Fig: 4.6 (b)

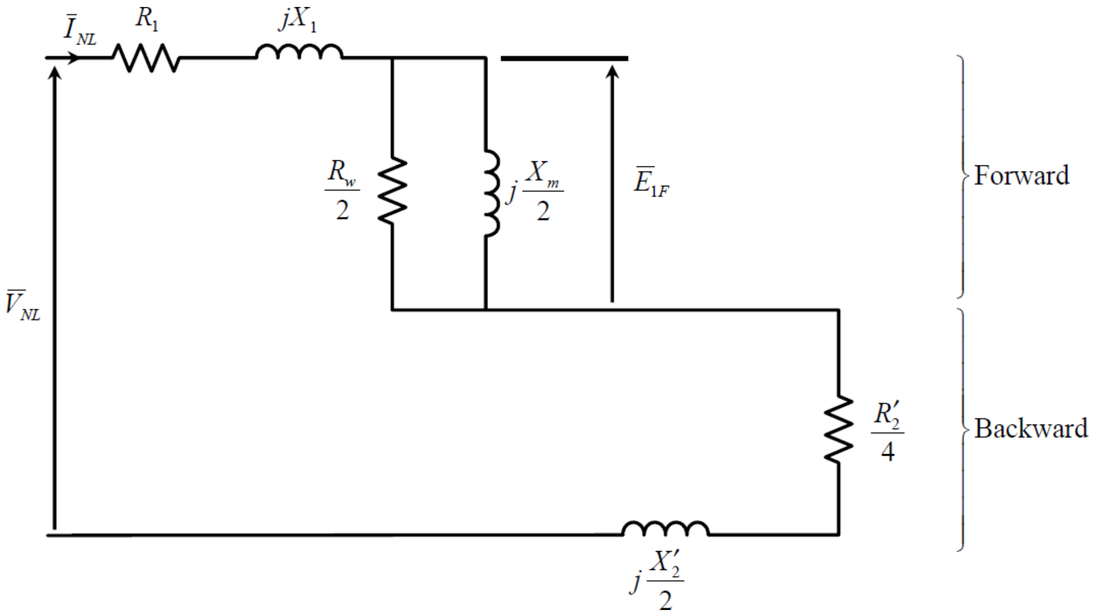


Fig: 4.6 (b) Rearranged approximate equivalent circuit of the single phase induction motor at no load

Then, R_w, and X_m, can be obtained as fallows:

$$P_{core+mechanical} = P_{NL} - I_{NL}^2\left(R_1 + \frac{R_2'}{4}\right)$$

$$\bar{E}_{1F} = \bar{V}_{NL} - \bar{I}_{NL}\left(\left(R_1 + \frac{R_2'}{4}\right) + j\left(X_1 + \frac{X_2'}{2}\right)\right)$$

Note: $(\bar{I}_{NL} = I_{NL}\angle -\theta, \quad \theta = \cos^{-1}\frac{P_{NL}}{V_{NL}\ I_{NL}})$

$$R_w = 2\frac{|E_{1F}|^2}{P_{core+mechanical}}$$

$$I_w = \frac{|E_{1F}|}{\left(\frac{R_w}{2}\right)} = 2\frac{|E_{1F}|}{R_w}$$

$$I_m = \sqrt{I_{NL}^2 - I_w^2}$$

$$X_m = 2\frac{|E_{1F}|}{I_m}$$

d) Shaped pole starting

The motor consists of a yoke to which salient poles are fitted as shown in Fig: 4.14(a) and it has a squirrel cage type rotor.

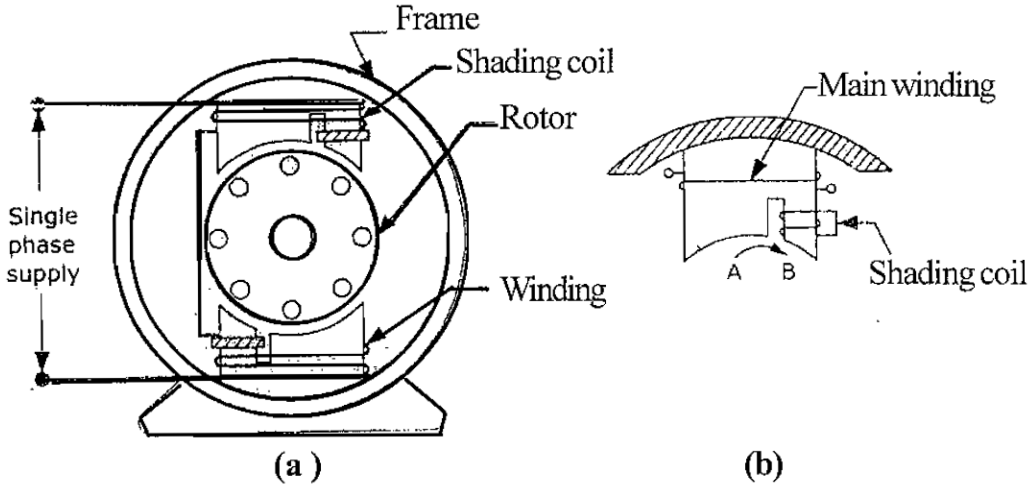


Fig: 4.14

A shaded pole made of laminated sheets has a slot cut across the lamination at about one third the distance from the edge of the pole.

Around the smaller portion of the pole, a short-circuited copper ring is placed which is called the shading coil, and this part of the pole is known as the shaded part of the pole. The remaining part of the pole is called the un shaded part which is clearly shown in Fig: 4.14(b).

Around the poles, exciting coils are placed to which an AC supply is connected. When AC supply is effected to the exciting coil, the magnetic axis shifts from the un shaded part of the pole to the shaded part as will be explained in details in the next paragraph. This shifting of axis is equivalent to the physical movement of the pole.

This magnetic axis, which is moving, cuts the rotor conductors and hence, a rotational torque is developed in the rotor.

By this torque the rotor starts rotating in the direction of the shifting of the magnetic axis that is from the un shaded part to the shaded part.

The magnetic flux shifting

As the shaded coil is of thick copper, it will have very low resistance but as it is embedded in the iron case, it will have high inductance. When the exciting winding is connected to an AC supply, a sine wave current passes through it.

Let us consider the positive half cycle of the AC current as shown in Fig: 4.15.

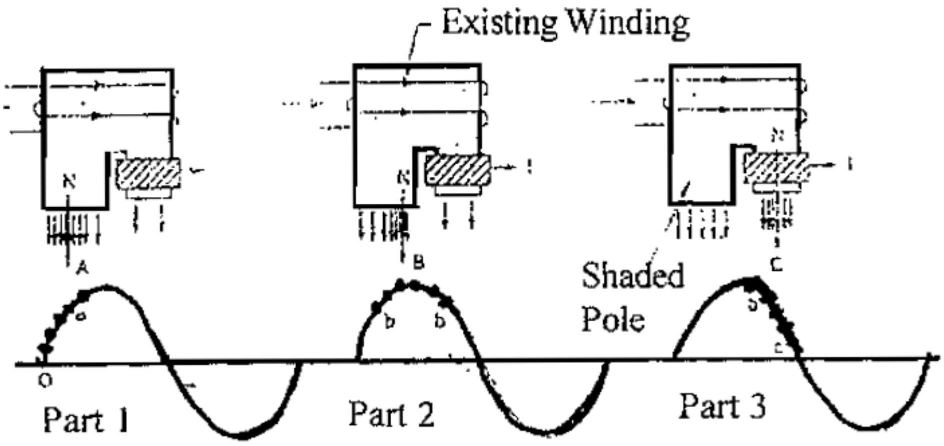


Fig: 4.15 Shifting of magnetic flux

When the current raises from "Zero" Value of point "0" to a point "a" the change in current is very rapid (Fast). Hence, it reduces an emf in the shaded coil on the basis of Faraday's law of electromagnetic induction.

The induced emf in the shaded coil produces a current which, in turn, produces a flux in accordance with Lenz Law. This induced flux opposes the main flux in the shaded portion and reduces the main flux in that area to a minimum value as shown in Fig: 4.15.

This makes the magnetic axis to be in the centre of the un shaded portion as shown by the arrow in part of Fig: 4.15. On the other hand as shown in part 2 of 3 when the current raises from point "a" to point "b" the change in current is slow the induced emf and resulting current in the shading coil is minimum and the main flux is able to pass through the shade portion.

This makes the magnetic axis to be shifted to the centre of the whole pole as shown in by the arrow in part 2 of Fig: 4.15.

In the next instant, as shown in part 3 of Fig: 4.15. When the current falls from "b" to "c" the change in current is fast but the change of current is from maximum to minimum.

Hence a large current is induced in the shading ring which opposes the diminishing main flux, thereby increasing the flux density in the area of the shaded part. This makes the magnetic axis to shift to the right portion of the shaded part as shown by the arrow in part.

From the above explanation it is clear the magnetic axis shifts from the un shaded part to the shaded part which is more or less a physical rotary movement of the poles. Simple motors of this type cannot be reversed. Specially designed shaded pole motors have been constructed for reversing operations. Two such types:

1) The double set of shading coils method
2) The double set of exciting winding method.

Shaded pole motors are built commercially in very small sizes, varying approximately from 1/250 HP to 1/6 HP. Although such motors are simple in construction and cheap, there are certain disadvantages with these motor as stated below:

a) Low starting torque.
b) Very little overload capacity.
c) Low efficiency.

Applications:

a) Record players
b) Fans
c) Hair driers.

MODULE IV

SYNCHRONOUS GENERATORS

Introduction

In electrical engineering particularly in power production there are 2 main sources of energy conversion, first is a motor and the other is a generator. The generator is a device that produces electrical energy and motor produce mechanical power. The motors and generators are further divided into the AC and DC motors and generators according to their power generation and use.

The synchronous generator is the type of AC generator. For energy generation in wind turbines, a steam turbine or hydro turbines synchronous generator is used. In today’s post we will have a look at its construction, working, excitation method, etc. so let’s get started with the introduction to a synchronous generator.

Introduction to Synchronous Generator

The synchronous generator is also known as an alternator, it converts the mechanical power into the electrical. The electric energy we used in our home or industries is mostly produced by the synchronous generator. There are many sources of energy conversion in the world but most of the energy is converted by the synchronous generator. They convert mechanical energy into the electrical energy up to the 1500 megawatt. The synchronous generators used in our industries are constructed by a static or rotating magnetic field. The construction of the synchronous generator built by the static field is like the DC generator.

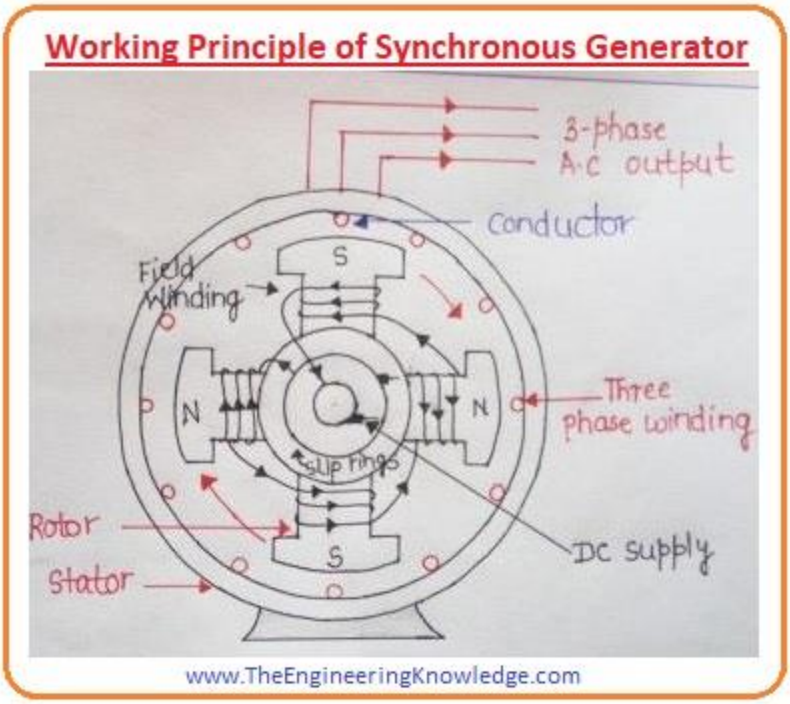
In the rotating magnetic field generator, the static armature is known as the rotor.

Working Principle of Synchronous Generator

The working of a synchronous generator is based on Faraday’s Law of electromagnetic induction.

emf= $d\Phi/dt$

This law says that the rate of change of flux in any device will produce emf in that device. If a device is static and the field is rotating it will also produce field in the device. In case of a synchronous generator, the rotor is rotating, and it produces field in the stator. For an understanding of emf induced in any device study the article on the voltage induced in the loop.


Working Principle of Synchronous Generator

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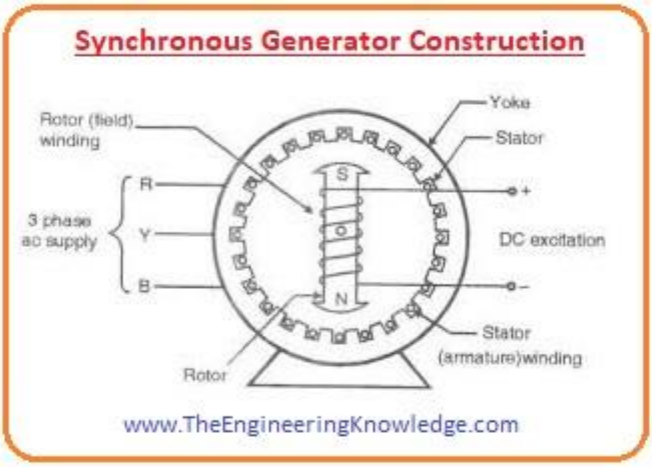
Synchronous Generator Construction

In a synchronous generator, there is no residual magnetism to produce self-excitation like the induction motor and induction generator. The external direct current supply is given to the rotor and it produces field in the rotor. When we rotate the rotor by mechanical way, its field link with the stator windings and produce a voltage in the stator. There are 2 terms we use to represent windings in the machines first one is armature winding and the other one is field winding.

The windings that produce the main field in a machine called field winding and the windings that produce voltage is called armature.

In case of the synchronous generator, the field windings are the rotor windings and the stator windings are the armature windings.


Synchronous Generator Construction

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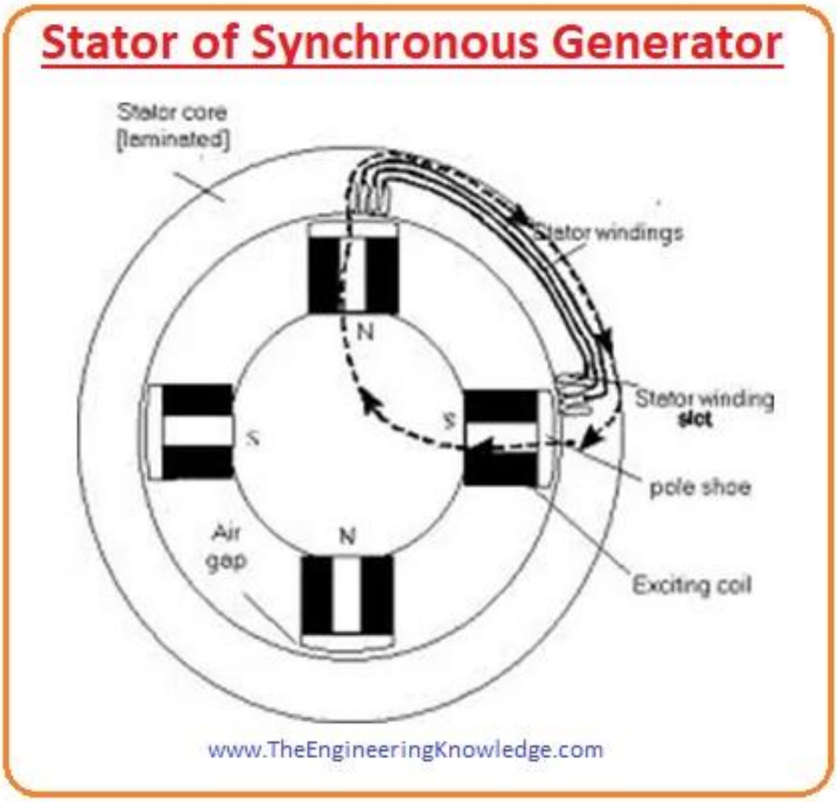
Stator Of Synchronous Generator

The stator is the static part of the generator it provides the covering to the internal construction of the machine.

It is constructed by the laminated sheets of aluminum, there are slots at its inner periphery which used to hold the windings.


Stator of Synchronous Generator

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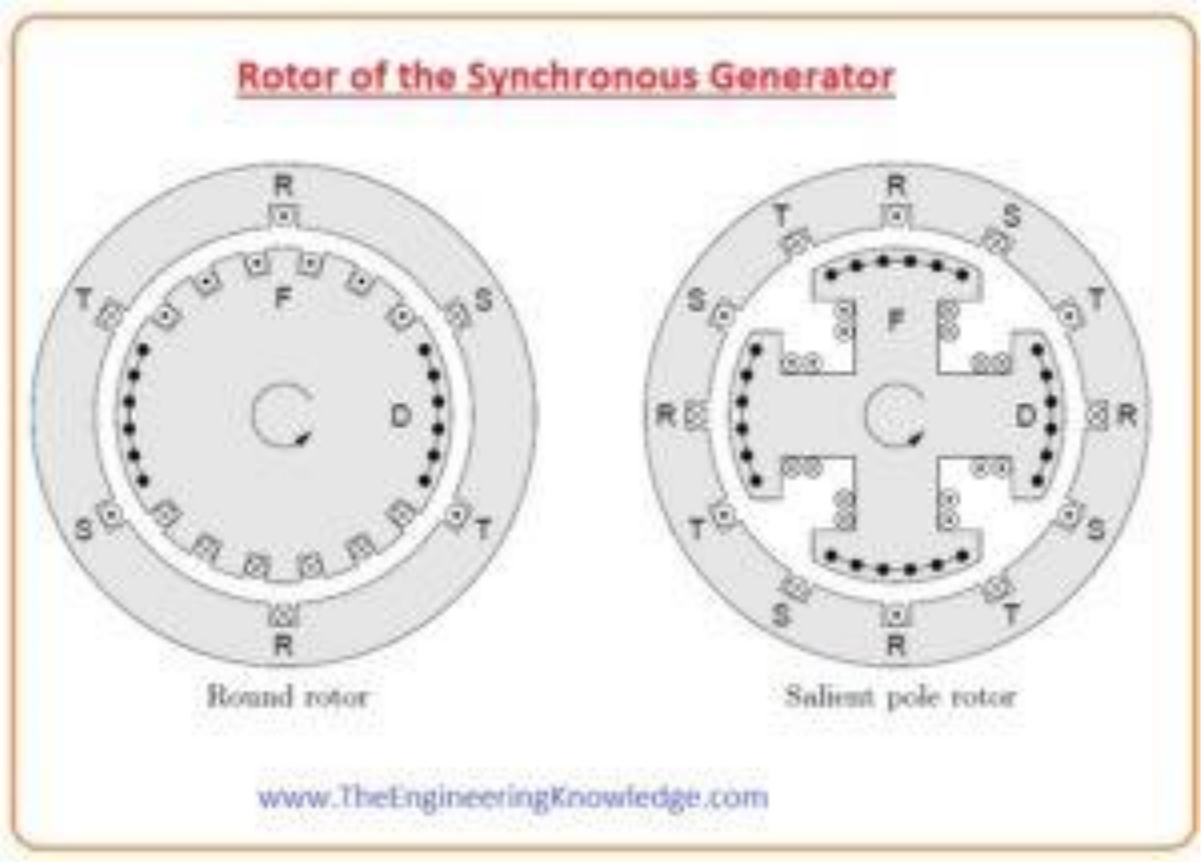
Rotor of the Synchronous Generator

The rotor of the generator is an electromagnet, it is connected with the external DC source. The external source produces a voltage in the rotor, the field of the rotor induced a voltage in the stator.



There are 2 main types of synchronous generator.

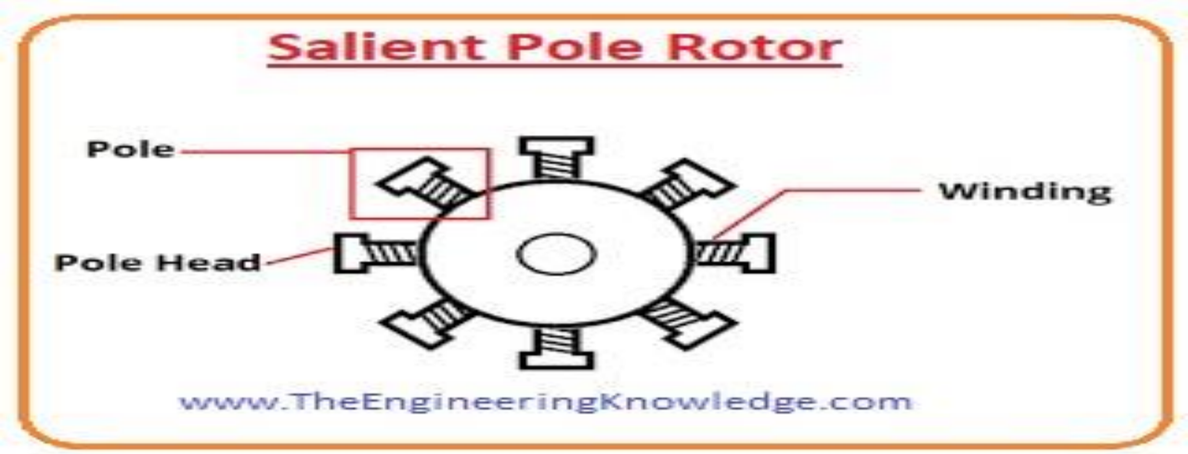
a) Salient Pole Rotor
b) Non-Salient Pole Rotor

a) Salient Pole Rotor

This type of rotor has many no of poles that are manufactured on the wheel like arrangements.

These poles are constructed from steel and are laminated. The windings of the rotor are wound on these poles and at the corners, windings are controlled by the pole shoe. The dia of the salient pole rotor is higher and its axis is short. The salient pole rotor has 4 or large no of the pole.

The given diagram shows the salient pole

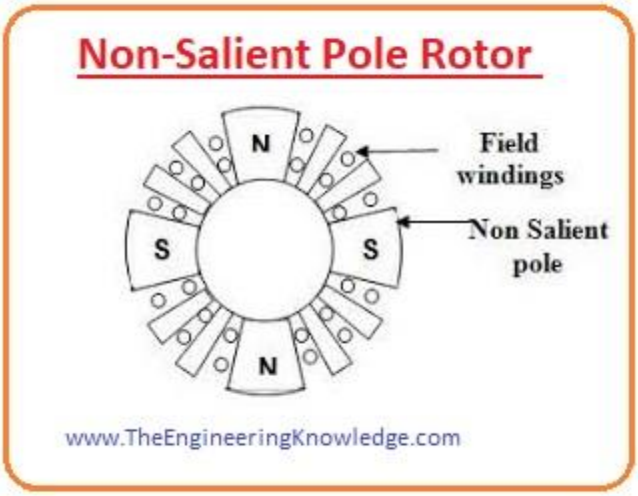


rotor.

b) Non-Salient Pole Rotor

The word ‘salient’ means to stick out, Non-salient pole is such a pole that is manufactured with the surface of the rotor they are not out of the surface like the salient poles.

This type of rotor is used where 4 or more poles are required at the stator.



DC Excitation Of Synchronous Generator

As we discussed that the synchronous generator is not a self-start machine. It must connect with the external source. To excitation of the generator, the DC supply is connected with the circuitry of the rotor. As the rotor rotates so there is some precaution that we should keep in mind, connecting rotor with the DC source. Try to connect the windings of the rotor with the DC source through the slip ring and graphite made brushes, if you connect the windings directly with the dc source, it causes serious spark and motor will damage.

Connect such dc source with the generator that remains permanently connected with the rotor.

The slip ring is rings made by some metal, they are mounted on the shaft of the generator and have some insulation.

Every end of the rotor’s windings is joined with the slip rings and the static brushes are mounted on the slip rings. The brushes always mounted on the slip ring because they are made from graphite which has less resistance. If the one terminal of the DC source is joined with one carbon brush, then the other will be connected with the second brush. The important thing you should note that the dc voltage you provided to the generator should have same value irrespective of the variation in the speed and angular position of the generator.

Problems of Slip Ring and Brushes in Synchronous Generator

As we discussed that we use slip ring and carbon brushes to provide the dc supply to the windings of the rotor. These two components cause some difficulties.

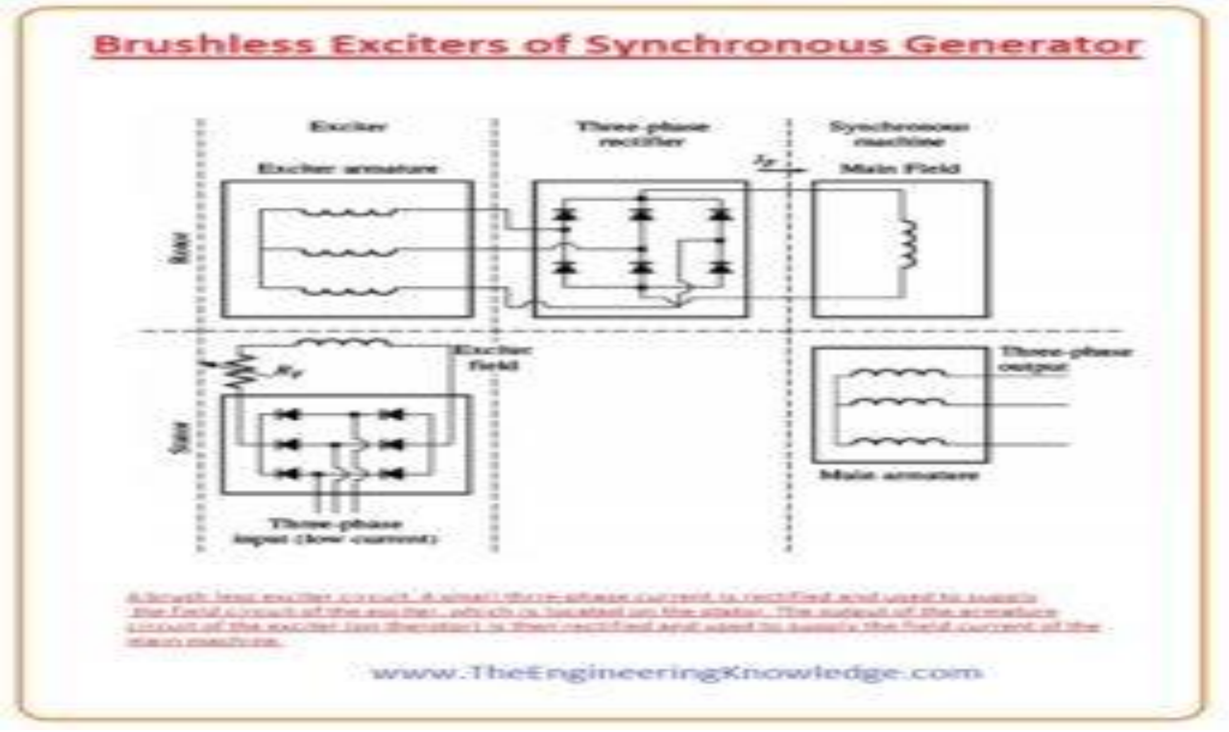
As the brush is made from the carbon that is soft material nature, so their condition must be monitored after some time and maybe they should be replaced after some time. This process increases the maintenance cost of the machine. There is some loss of voltage at the brushes which increases the field current and power loss at the field windings. For a smaller synchronous machine this method of the voltage is used because it is a cheap method for these machines.

Brushless Exciters Of Synchronous Generator

The slip ring and brush technique do not work for the larger motor and generator. For dc supply to the rotor, they used brushless exciters. The brushless exciter is itself an ac generator, as any machine has 2 circuitries, first is armature and other is field. When this exciter relates to any synchronous machine, its field circuitry resides on the static part of the synchronous machine and armature circuitry mounted on the shaft of the machine.

As the output of the exciter is 3 phase ac which is then converted to dc by the rectification, this rectification circuitry is also connected on the shaft of the synchronous generator. Then the output of the rectifier sent to the field circuitry of the rotor. By varying the field current of the exciter, we can easily control the field current of the synchronous generator.

As there is no physical connection among the stator and rotor of the generator, so the exciter needs a very lesser amount of repairing then slip ring and brushes.The arrangement of the brushless exciter with a generator is shown in a given diagram.

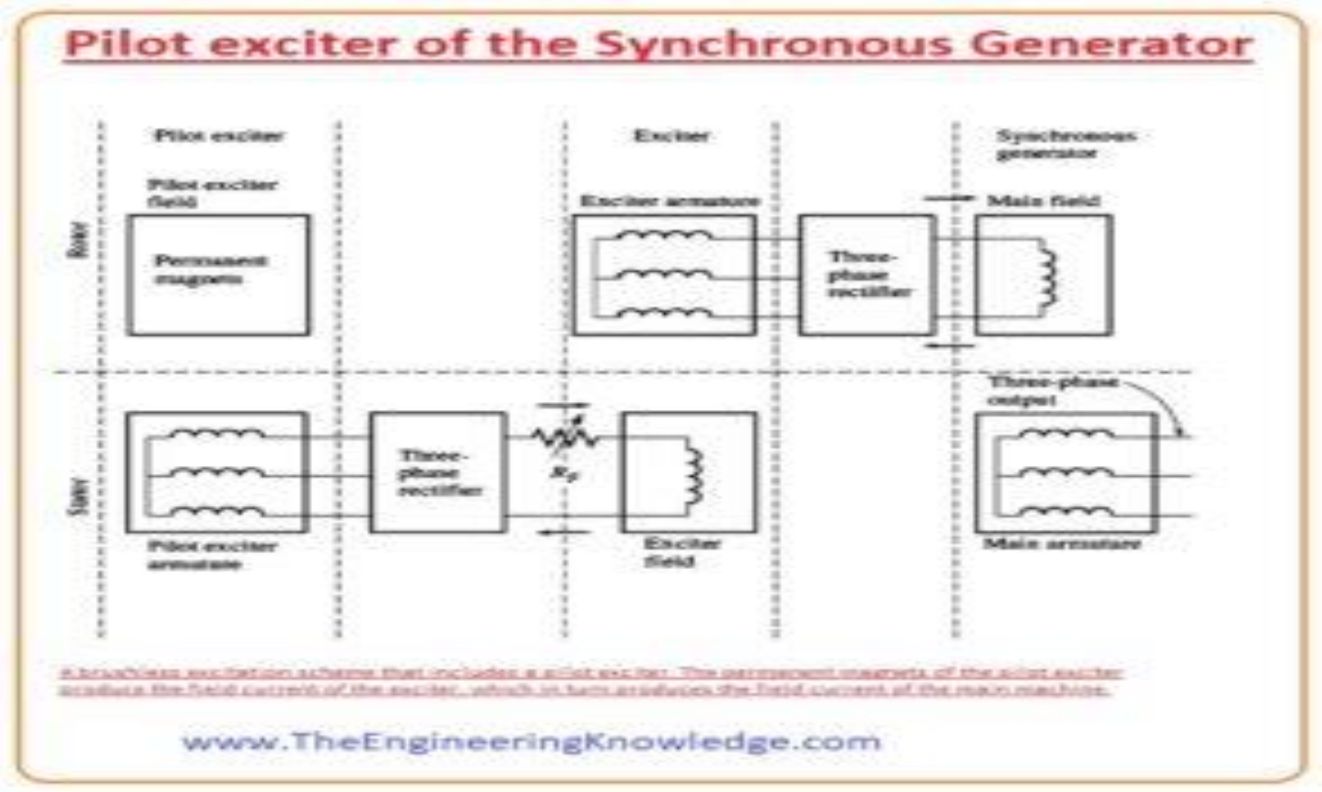


Pilot exciter of the Synchronous Generator

To make the construction of the synchronous generator simplest and excitation of the generator independent from the exterior circuitry a pilot exciter introduced on the machine. Pilot exciter is also an alternating current generator it has permanent magnet instead of the armature circuitry which connected with the shaft and its 3 phase windings are joined with the stator.

It generates the power for the exciter's field circuitry, this power then governs the field circuitry of the generator. If a pilot exciter relates to the shaft of the rotor then there will be no need of the exterior power supply to operate the generator. Most of the synchronous generator also has a slip ring and brushes with the brushless exciter, in case of an emergency backup power supply is exists.

A given diagram shows the pilot exciter circuit.



Speed of Rotation of a Synchronous Generator

As we have discussed that the rotor of the synchronous generator is an electromagnet, it joined to the dc source.The direction of the field of the rotor will be the direction of the rotation of the rotor.

The speed rotation of the field in the ac machine has a relation with the frequency at the stator, is given as.

$f_e = n_m P/120$

f_e in this equation is the frequency of the stator.

n_m it is the speed of the field.

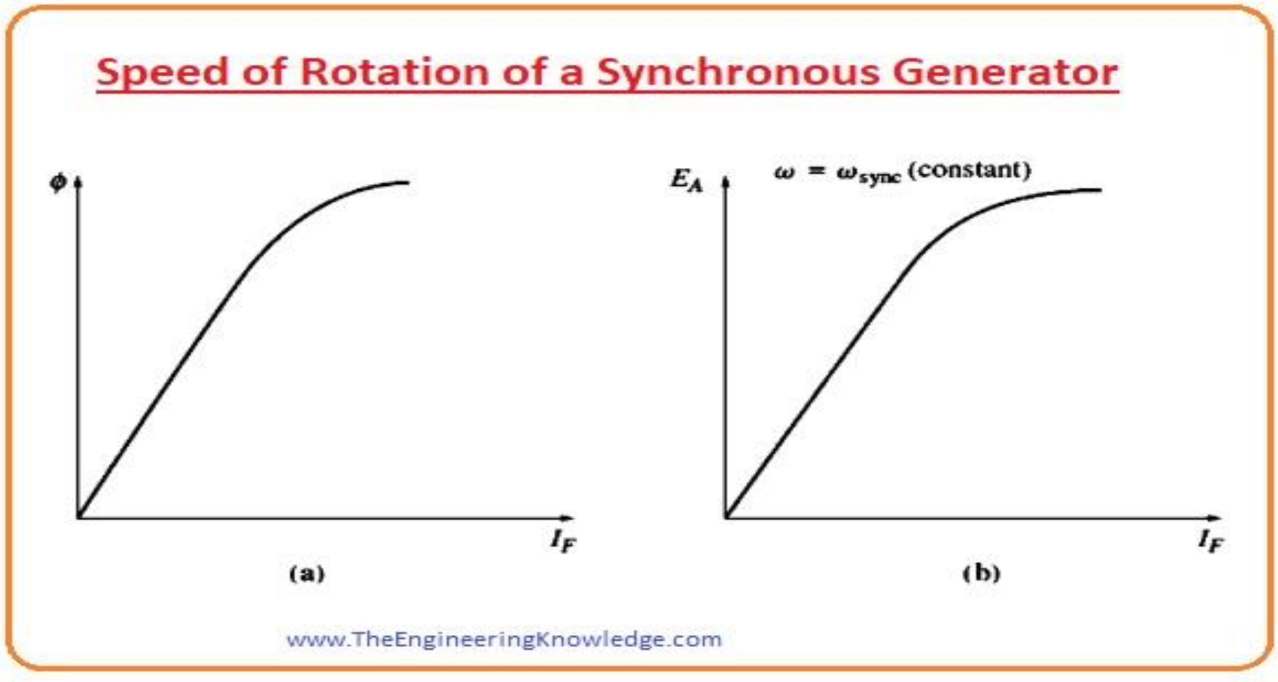
P is the no of poles

As the speed of the rotation of the rotor is equal to the speed of the field, this equation shows the relation of the rotor speed to the frequency of the stator.

The electrical energy generated at the fifty or sixty-hertz frequencies, so the generator should move at the constant speed.

For example, to produce the sixty-hertz energy in a 2-pole machine the speed of the rotor should be 3600 revolutions per minute.

And to produce the fifty-hertz energy in a 4-pole machine the speed of the rotor should be 1500 revolution per minute.



Synchronous Generator Vs Induction Generator

These are some similarities and dissimilarities between synchronous and induction generators that are described here.

i) In synchronous generator, the speed of rotation of the rotor is equal to the speed of the rotation of the field at the stator.

$$f = (N \times P)/120$$

But in the case of a synchronous generator, the frequency of output voltage is controlled by the power system with which it linked.

ii) The synchronous generator is not self-excited there is a need of special direct current source to connected with it.

iii) While there is no need of a special external source for the induction generator, as it is self start the machine.

The presence of carbon brushes and separate dc sources make complicated construction of a synchronous generator and increase its price.

iv) But the induction generator is self start and there is no need of carbon brushes and slip ring so its construction is simplest and its maintenance price is also less.

Cooling of Synchronous Generator

When the generator is operated at heavy load then huge amount of heat produces in the generator that can be caused of dangerous for the internal structure of the synchronous generator.

To reduce or minimize heat in the generator there are several methods are used that are described here.

a) Radial Flow Ventilation System

In this type of cooling method cool air is passed through the stator with the ducts and from another side of the stator it comes out.

Advantages of Radial Ventilation

i) In this method of cooling power losses for ventilation is less.

ii) It can be used for both less ratings and high rating generators.

b) Hydrogen Cooling of a Synchronous Generator

In this method, hydrogen is used for the cooling of a generator. Before its use for cooling its ratio with air must be controlled and keep (9/1) hydrogen to air. As if the air exists in environments where hydrogen is performed it can create expulsion.

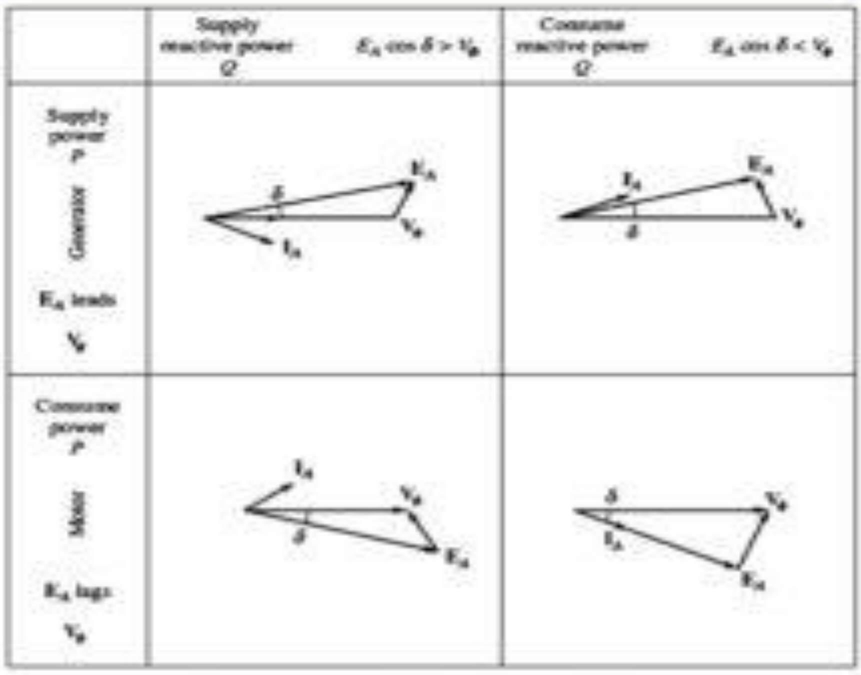
Difference between Synchronous Motor and Synchronous Generator

i) The synchronous generator is such a device that transforms mechanical energy provided by the prime mover to electrical power, but motor transforms electrical into mechanical energy.

ii) But these to the motor are similar in physical structure.

iii) Any synchronous machine either motor or a generator can provide active power to or get active power from a system connected and provide reactive power to and get reactive power from the system.

All these 4 possibilities of these machines are shown in a given figure in the shape of the phasor diagram.



Phasor diagrams showing the generation and consumption of real power P and reactive power Q by synchronous generators and motors.

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The unique feature of a synchronous generator (providing P) is that internal generated voltage E_A lies ahead Vø, but in case of a motor internal generated voltage, E_A lies behind Vø.

The different feature a machine (either generator or motor) providing reactive power Q is that $E_A\cos\delta >$ Vø, irrespective of whether the machine is acting as a generator or as a motor. A machine that is taking Q has $E_A\cos\delta <$ Vø.

Applications Of Synchronous Generator

These are some applications of synchronous generators that are described here.

i) It mostly used in such a system where constant speed is required.

ii) They also maintain the power factor of the system.

iii) Almost all power generation plants use synchronous generators due to constant frequency providing the capability.

Emf Equation Of A Synchronous Generator

The generator which runs at a synchronous speed is known as the synchronous generator. The synchronous generator converts the mechanical power into electrical energy for the grid. The Derivation of EMF Equation of a synchronous generator is given below.

Let,

P be the number of poles

ϕ is Flux per pole in Webers

N is the speed in revolution per minute (r.p.m)

f be the frequency in Hertz

Z_{ph} is the number of conductors connected in series per phase

T_{ph} is the number of turns connected in series per phase

K_c is the coil span factor

K_d is the distribution factor

Flux cut by each conductor during one revolution is given as Pϕ Weber. Time taken to complete one revolution is given by 60/N sec

Average EMF induced per conductor will be given by the equation shown below:

$$\frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts}$$

Average EMF induced per phase will be given by the equation shown below:

$$\frac{P\varphi N}{60} \text{ x } Z_{ph} = \frac{P\varphi N}{60} \text{ x } 2T_{ph} \quad \text{and}$$

$$T_{ph} = \frac{Z_{ph}}{2}$$

$$\text{Average EMF} = 4 \text{ x } \varphi \text{ x } T_{ph} \text{ x } \frac{PN}{120} = 4\varphi f T_{ph}$$

The average EMF equation is derived with the following assumptions given below.

Coils have got the full pitch.

All the conductors are concentrated in one stator slot.

Root mean square (R.M.S) value of the EMF induced per phase is given by the equation shown below:

E_{ph} = Average value x form factor

Therefore,

$$E_{ph} = 4\varphi f T_{ph} \text{ x } 1.11 = 4.44\ \varphi\ f\ T_{ph} \quad \text{volts}$$

If the coil span factor K_c and the distribution factor K_d , are taken into consideration then the Actual EMF induced per phase is given as:

$$E_{ph} = 4.44\, K_c K_d \varphi\, f\, T_{ph} \text{ volts} \;\ldots\ldots\ldots(1)$$

Equation (1) shown above is the EMF equation of the Synchronous Generator.

Coil Span Factor

The Coil Span Factor is defined as the ratio of the induced emf in a coil when the winding is short-pitched to the induced emf in the same coil when the winding is full pitched.

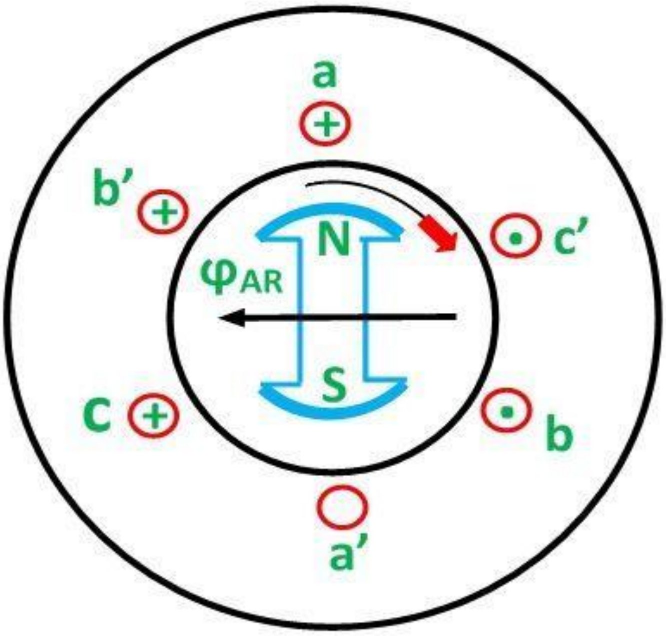
Distribution Factor

The distribution factor is defined as the ratio of induced EMF in the coil group when the winding is distributed in a number of slots to the induced EMF in the coil group when the winding is concentrated in one slot.

Armature Reaction In A Synchronous Machine

The effect of Armature (stator) flux on the flux produced by the rotor field poles is called Armature Reaction**.** When the current flows through the armature winding of the an alternator, a flux is produced by the resulting MMF. This armature flux reacts with the main pole flux, causing the resultant flux to become either less than or more than the original main field flux.

For simplicity, we consider a 3 phase, 2 pole alternator shown in the figure below.



Circuit Globe

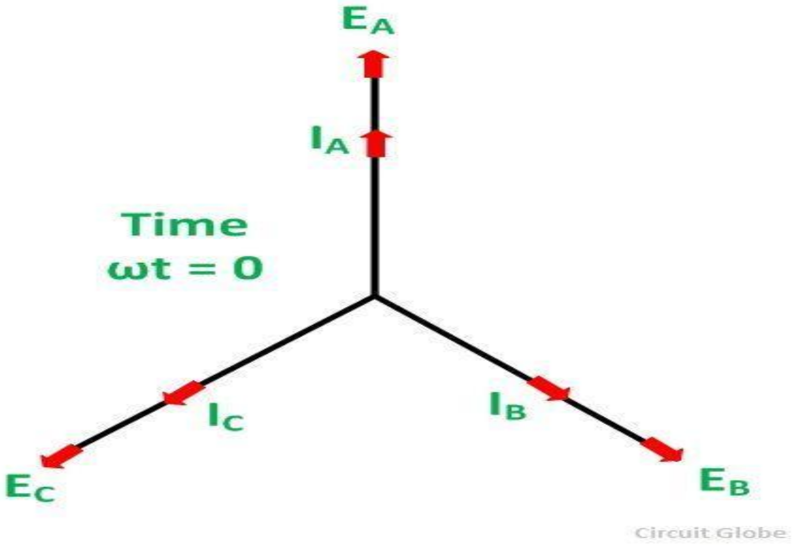
The winding of each pole is assumed to be concentrated, but the effects of armature reaction will be the same as if a distributed winding were also used. The armature reaction in synchronous machine affects the main field flux and vary differently for different power factors.

Here armature reaction is discussed for following three conditions, namely unity power factor, zero power factor lagging and zero power factor leading. The power factor can be defined as the cosine of the angle between the armature phase current and the induced EMF in the armature conductor in that phase.

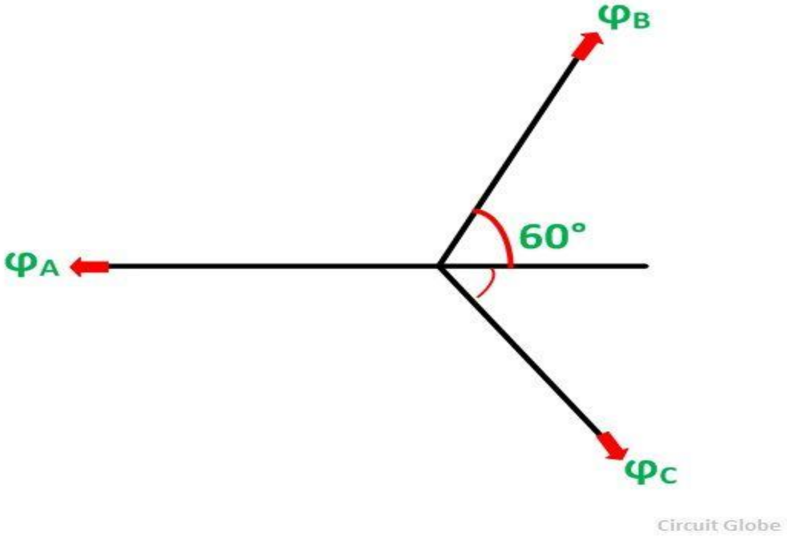
Armature Reaction At Unity Power Factor

The direction of rotation of the rotor is considered clockwise. By applying right hand rule, the direction of the induced emf in various conductors can be found. The direction of rotation of the conductors is taken anticlockwise with respect to the rotor poles.

Suppose that the alternator is supplying current at unity power factor. The phase current I_A, I_B, and I_C will be in phase with their respective generated voltages, i.e., E_A, E_B, and E_C as shown in the figure below.



The positive direction of fluxes ϕ_A, ϕ_B, ϕ_C are shown in the figure below.



The projection of a phasor on the vertical axis gives its instantaneous value.

At **t=0**, the instantaneous values of currents and fluxes are given by the equation shown

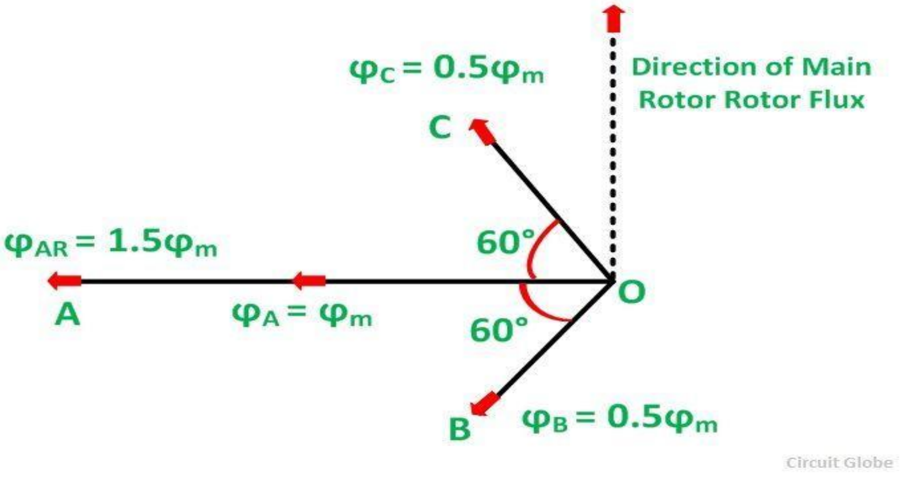
$$i_A = I_m \text{ and } \varphi_A = \varphi_m$$

$$i_B = -I_m \operatorname{Cos} 60^\circ = -\frac{1}{2} I_m \quad \text{and} \quad \varphi_B = -\frac{1}{2}\varphi_m$$

$$i_C = -I_m \operatorname{Cos} 60^\circ = -\frac{1}{2} I_m \quad \text{and} \quad \varphi_C = -\frac{1}{2}\varphi_m$$

below.

Where the subscript m denotes the maximum values of current and flux. Thus, the flux ϕ_A is along OA and the fluxes ϕ_B and ϕ_C are negative and acts opposite to each other represented by OB and OC respectively as shown in the figure below. The resultant of the fluxes can be found by resolving the fluxes horizontally and vertically.



Resolving along the horizontal direction we

$$\varphi_h = -\varphi_A - \varphi_B \cos 60^\circ - \varphi_C \cos 60^\circ$$

$$\varphi_h = -\varphi_m - \left(\frac{1}{2}\varphi_m\right)\left(\frac{1}{2}\right) - \left(\frac{1}{2}\varphi_m\right)\left(\frac{1}{2}\right)$$

$$\varphi_h = -1.5\,\varphi_m$$

get

Similarly,

resolving along the vertical direction we

$$\varphi_v = -\varphi_B \cos 30° + \varphi_C \cos 30°$$

$$\varphi_v = -\frac{1}{2}\varphi_m \cos 30° + \frac{1}{2}\varphi_m \cos 30° = 0$$

get

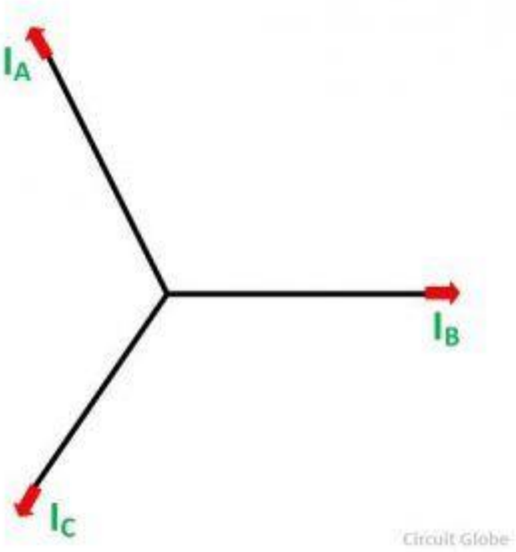
The resultant armature reaction flux is given

$$\varphi_{AR} = \sqrt{\varphi_h^2 + \varphi_v^2} = \sqrt{(1.5\,\varphi_m)^2 + 0}$$

$$\varphi_{AR} = 1.5\,\varphi_m$$

by

If the rotor is rotated, 30 degrees in a clockwise direction, the corresponding phasor diagram is shown below.



At the instant when **ωt = 30⁰**, the instantaneous values of currents and fluxes are given

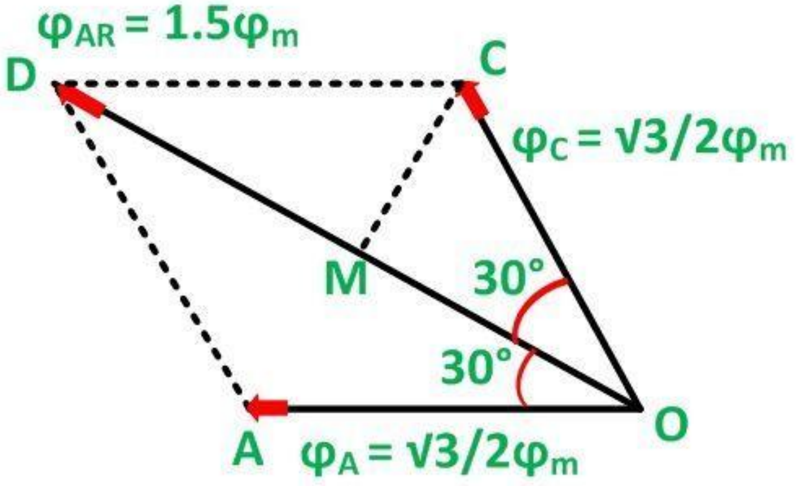
$$i_A = I_m \cos 30° = \frac{\sqrt{3}}{2} I_m \quad \text{and} \quad \varphi_A = \frac{\sqrt{3}}{2}\varphi_m$$

$$i_B = 0 \quad \text{and} \quad \varphi_B = 0$$

$$i_C = -I_m \cos 30° = -\frac{\sqrt{3}}{2} I_m \quad \text{and} \quad \varphi_C = -\frac{\sqrt{3}}{2}\varphi_m$$

as

The space diagram for fluxes at ωt = 30° is shown below.



Circuit Globe

Here, ϕ_B = 0. The resultant armature reaction flux is given by the equation shown below.

$$\varphi_{AR} = OD = 2\,OM$$

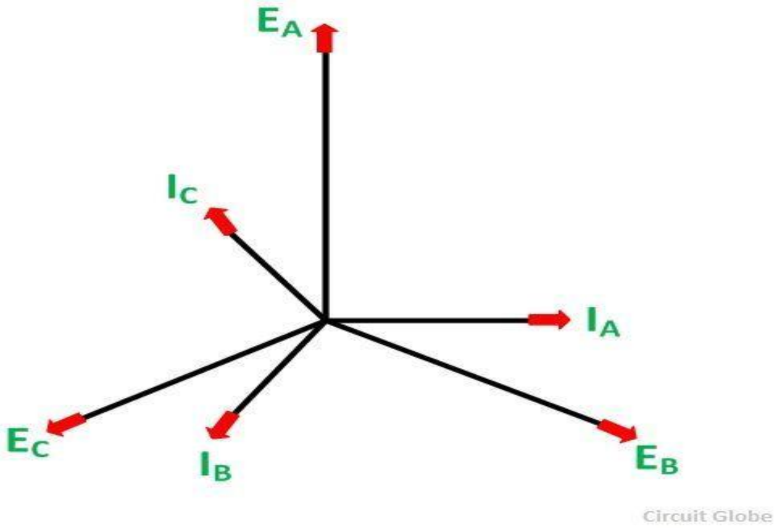
$$\varphi_{AR} = 2\,OC\cos 30^0 = 2\left(\frac{\sqrt{3}}{2}\,\varphi_m\right)\frac{\sqrt{3}}{2} = 1.5\,\varphi_m$$

The direction of the resultant flux ϕ_{AR} is along OD, which makes an angle with the horizontal in the clockwise direction.

Hence, it is observed that the resultant flux ϕ_{AR} sets up by the current in the armature remains constant in magnitude equal to 1.5 ϕ_m and it rotates at synchronous speed. When the current is in phase with the induced voltage the armature reaction flux ϕ_{AR} lags behind the main field by 90°. This is called **Cross Magnetizing Flux.**

Armature Reaction at Lagging Power Factor

If the alternator is loaded with an inductive load of zero power factor lagging. The phase current I_A, I_B and I_C will be lagging with their respective phase voltages E_A, E_B and E_C by 90°. The figure below shows the phasor diagram of armature reaction at lagging load.



At time **t** = **0**, the instantaneous values of currents and fluxes are given

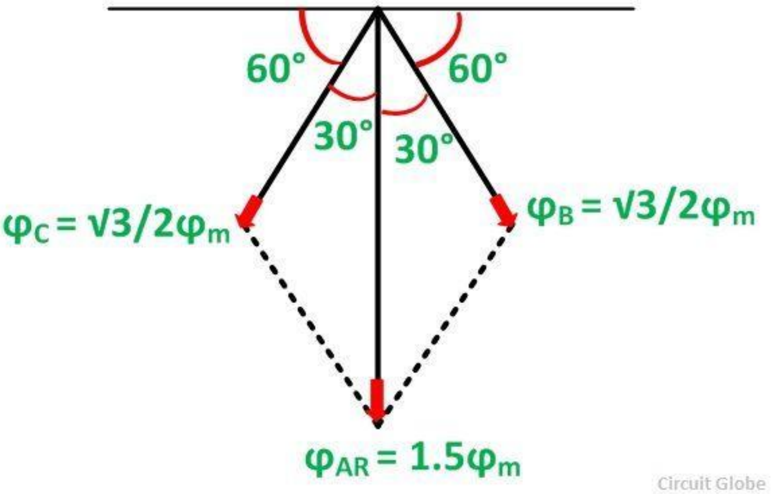
$$i_A = 0 \quad \text{and} \quad \varphi_A = 0$$

$$i_B = I_m \sin(-120°) = -\frac{\sqrt{3}}{2} I_m \quad \text{and} \quad \varphi_B = -\frac{\sqrt{3}}{2}\varphi_m$$

$$i_C = I_m \sin(+120°) = \frac{\sqrt{3}}{2} I_m \quad \text{and} \quad \varphi_C = \frac{\sqrt{3}}{2}\varphi_m$$

by

The space diagram of the magnetic fluxes is shown below.



The resultant flux ϕ_{AR} is given by the equation shown below.

$$\varphi_{AR}^2 = \varphi_R^2 + \varphi_C^2 + 2\varphi_R\varphi_C \cos 60^\circ$$

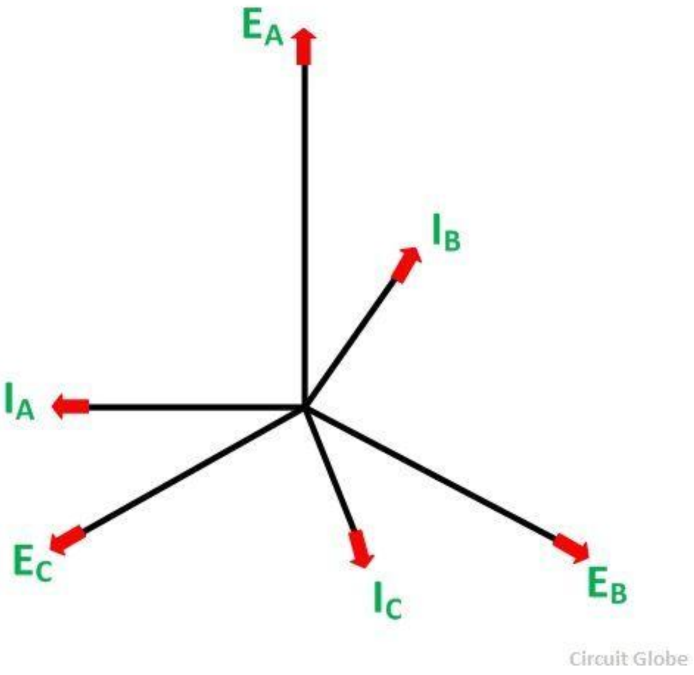
$$\varphi_{AR}^2 = \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + 2\left(\frac{\sqrt{3}}{2}\varphi_m\right)\left(\frac{\sqrt{3}}{2}\varphi_m\right) x \frac{1}{2}$$

$$\varphi_{AR} = 1.5\,\varphi_m$$

The direction of the armature reaction flux is opposite to the main field flux. Therefore, it will oppose and weaken the main field flux. It is said to be demagnetized.

Armature Reaction at Leading Power Factor

If the alternator is loaded with a load of zero power factor leading. The phase currents I_A, I_B and I_C will be leading their respective phase voltages E_A, E_B and E_C by 90º. The phasor diagram is shown below.



At time t = 0, the instantaneous values of currents and fluxes are given by the equations shown

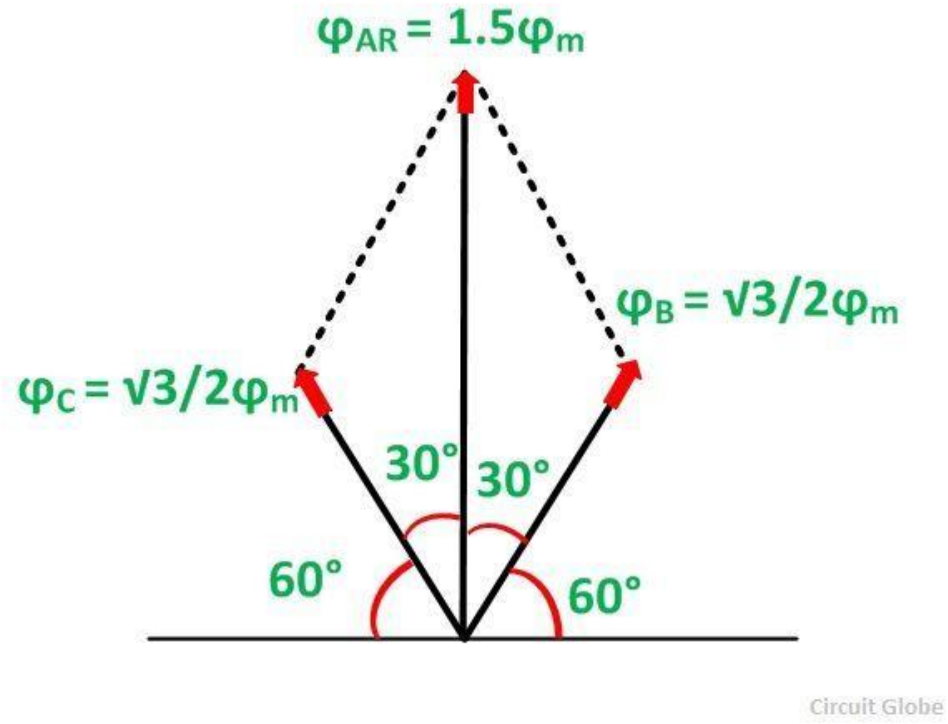
$$i_A = 0 \quad \text{and} \quad \varphi_A = 0$$

$$i_B = I_m \cos 30^0 = \frac{\sqrt{3}}{2} I_m \quad \text{and} \quad \varphi_B = \frac{\sqrt{3}}{2}\varphi_m$$

$$i_C = -I_m \cos 30^0 = -\frac{\sqrt{3}}{2} I_m \quad \text{and} \quad \varphi_C = -\frac{\sqrt{3}}{2}\varphi_m$$

below.

The direction of the flux is shown below in the phasor diagram.



The resultant flux is given by the equation shown below.

$$\varphi_{AR}^2 = \varphi_B^2 + \varphi_C^2 + 2\varphi_B\varphi_C \cos 60^\circ$$

$$\varphi_{AR}^2 = \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\varphi_m\right)^2 + 2\left(\frac{\sqrt{3}}{2}\varphi_m\right)\left(\frac{\sqrt{3}}{2}\varphi_m\right) \text{x} \frac{1}{2}$$

$$\varphi_{AR} = 1.5\,\varphi_m$$

The direction of the armature reaction flux is in the direction of main field flux. It is known as **magnetizing flux.**

Armature Reaction Nature

The following conclusion is given below.

i) The armature reaction flux is constant in magnitude and rotates at synchronous speed.

ii) The armature reaction is cross-magnetizing when the generator supplies a load at unity power factor.

iii) When the generator supplies a load, at lagging power, the armature reaction is partly demagnetizing and partly cross-magnetizing.

Methods of finding Voltage Regulation in Synchronous Generator

1. Direct loading method 2. EMF method or Synchronous impedance method 3. MMF method or Ampere turns method 4. ASA modified MMF method 5. ZPF method or Potier triangle method

Voltage Regulation

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

% Regulation =(E-V)/V*100

where E0 = No-load induced emf /phase, Vt = Rated terminal voltage/phase at load

Methods of finding Voltage Regulation:

The voltage regulation of an alternator can be determined by different methods. In case of small generators it can be determined by direct loading whereas in case of large generators it cannot determined by direct loading but will be usually predetermined by different methods. Following are the different methods used for predetermination of regulation of alternators.

1.Direct loading method

2.EMF method or Synchronous impedance method

3.MMF method or Ampere turns method

4. ASA modified MMF method

5.ZPF method or Potier triangle method

All the above methods other than direct loading are valid for non-salient pole machines only. As the alternators are manufactured in large capacity direct loading of alternators is not employed for determination of regulation. Other methods can be employed for predetermination of regulation. Hence the other methods of determination of regulations will be discussed in the following sections.

1. EMF 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's are to be determined. Armature resistance /phase of the alternator, open circuit and short circuit characteristics of the alternator.

Determination of synchronous impedance Zs

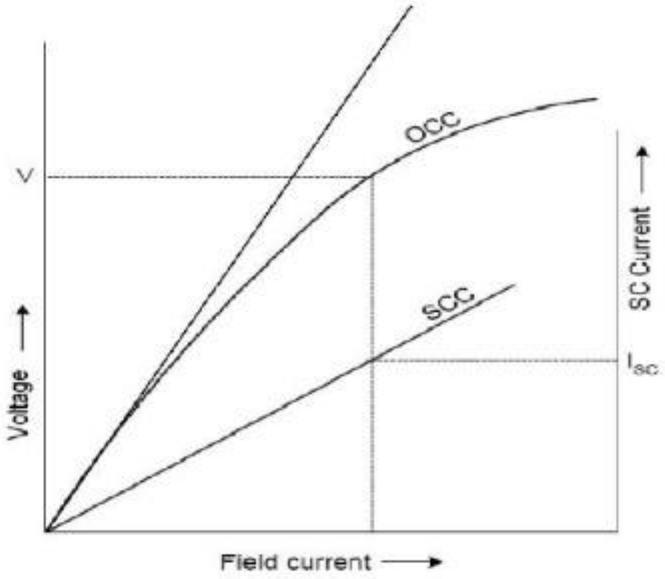


Fig: 1.16 OCC and SCC of alternator

As the terminals of the stator are short circuited in SC test, the short circuit current is circulated against the impedance of the stator called the synchronous impedance. This impedance can be estimated form the OC and SC characteristics.

The ratio of open circuit voltage to the short circuit current at a particular field current, or at a field current responsible for circulating the rated current is called the synchronous impedance.

Synchronous impedance Zs = (open circuit voltage per phase)/(short circuit current per phase) for same If

Hence Zs = (Voc) / (Isc) for same If

From Fig: 1.16 synchronous impedance Zs = V/Isc
Armature resistance Ra of the stator can be measured using Voltmeter - Ammeter method. Using synchronous impedance and armature resistance synchronous reactance and hence regulation can be calculated as follows using emf method.

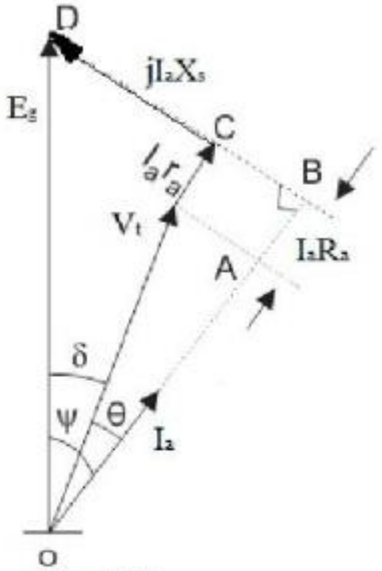


Fig: 1.17

$Z_s = \sqrt{[(R_a)^2 + (XS)^2]}$ and Synchronous reactance $X_s = \sqrt{[(Z_s)^2 - (R_a)^2]}$

Hence induced emf per phase can be found as $Eg = \sqrt{[(Vt\cos\theta + IaR_a)^2 + (Vt\sin\theta \pm IaXS)^2]}$

where Vt = phase voltage per phase = Vph , Ia = load current per phase

In the above expression in second term + sign is for lagging power factor and - sign is for leading power factor.

% Regulation = [Eg – Vt] / Vt

where

Eg = no-load induced emf /phase,

Vt = rated terminal voltage/phase

Synchronous impedance method is easy but it gives approximate results. This method gives the value of regulation which is greater (poor) than the actual value and hence this method is called pessimistic method. The complete phasor diagram for the emf method is shown in Fig 1.18.

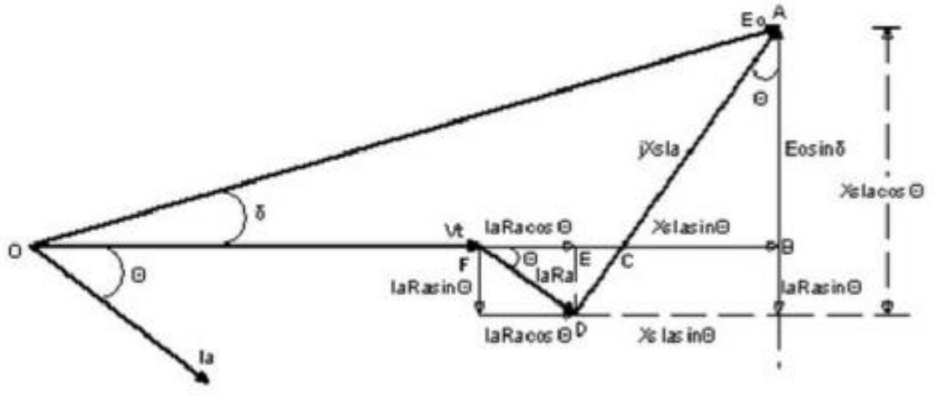


Fig: 1.18

2. MMF method

This method is also known as amp - turns method. In this method the all the emfs produced by rotor and stator are replaced by their equivalent MMFs (fluxes), and hence called mmf method. In this method also it is assumed that the magnetic circuit is unsaturated. In this method both the reactance drops are replaced by their equivalent mmfs. Fig: 1.19 shows the complete phasor diagram for the mmf method. Similar to emf method OC and SC characteristics are used for the determination of regulation by mmf method. The details are shown in Fig: 1.19. Using the details it is possible determine the regulation at different power factors.

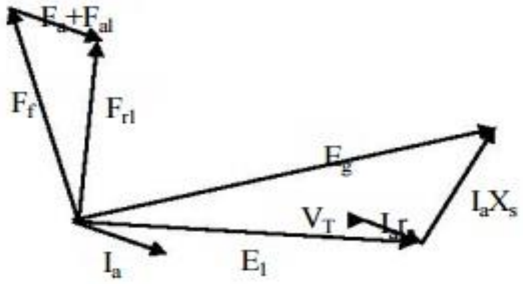


Fig: 1.19

From the phasor diagram it can be seen that the mmf required to produce the emf E1= (V + IRa) is FR1.In large machines resistance drop may neglected. The mmf required to overcome the reactance drops is (Fa+Fal) as shown in phasor diagram. The mmf (Fa+Fal) can be found from SC characteristic as under SC condition both reactance drops will be present.

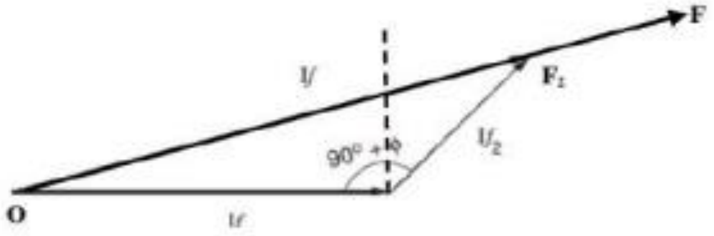
Following procedure can be used for determination of regulation by mmf method.

1. By conducting OC and SC test plot OCC and SCC.
2. From the OCC find the field current *If1* required to produce the voltage, E1= (V + IR_a).
3. From SCC find the magnitude of field current *If2* (≈F_a+F_{al}) to produce the required armature current. F_a+F_{al} can also found from ZPF characteristics.
4. Draw *If2* at angle (90+Φ) from *If1*, where Φ is the phase angle of current w. r. t voltage. If current is leading, take the angle of *If2* as (90-Φ).
5. Determine the resultant field current, *If* and mark its magnitude on the field current axis.
6. From OCC. find the voltage corresponding to *If,* which will be *E0* and hence find the regulation.

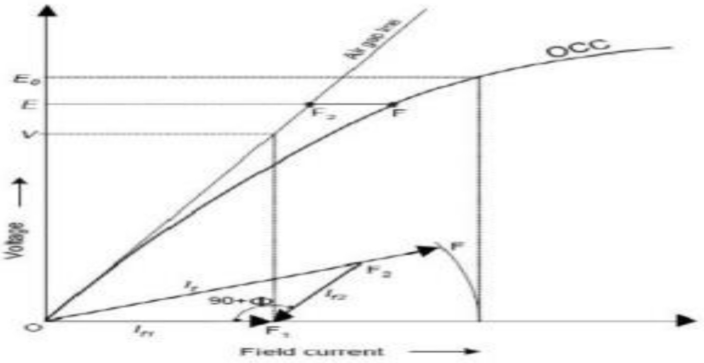
Because of the assumption of unsaturated magnetic circuit the regulation computed by this method will be less than the actual and hence this method of regulation is called optimistic method.

3. ASA Modified MMF Method:

ASA or modified mmf method consider saturation effect for calculation of regulation. In the mmf method the total mmf F computed is based on the assumption of unsaturated magnetic circuit which is unrealistic. In order to account for the partial saturation of the magnetic circuit it must be increased by a certain amount FF2 which can be computed from occ, scc and air gap lines as explained below referring to Fig: 1.20 (i) and (ii).



(i)



(ii)

Fig: 1.20

If1 is the field current required to induce the rated voltage on open circuit. Draw If2 with length equal to field current required to circulate rated current during short circuit condition at an angle (90+) from If1. The resultant of If1 and If2 gives If (OF2 in figure). Extend OF2 upto F so that F2F accounts for the additional field current required for accounting the effect of partial saturation of magnetic circuit. F2F is found for voltage E (refer to phasor diagram of mmf method) as shown in Fig: 1.20. Project total field current OF to the field current axis and find corresponding voltage E0 using OCC. Hence regulation can found by ASA method which is more realistic.

4. Zero Power Factor (ZPF) method or Potier Triangle Method:

During the operation of the alternator, resistance voltage drop IaRa and armature leakage reactance drop IaXL are actually emf quantities and the armature reaction reactance is a mmf quantity. To determine the regulation of the alternator by this method OCC, SCC and ZPF test details and characteristics are required. AS explained earlier oc and sc tests are conducted and OCC and SCC are drawn. ZPF test is conducted by connecting the alternator to ZPF load and exciting the alternator in such way that the alternator supplies the rated current at rated voltage running at rated speed. To plot ZPF characteristics only two points are required. One point is corresponding to the zero voltage and rated current that can be obtained from scc and the other at rated voltage and rated current under zpf load. This zero power factor curve appears like OCC but shifted by a factor IaXL vertically and horizontally by armature reaction mmf as shown below in Fig: 1.21. Following are the steps to draw ZPF characteristics.

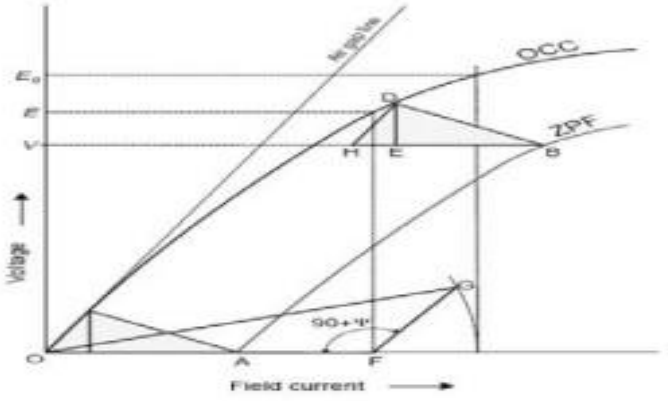
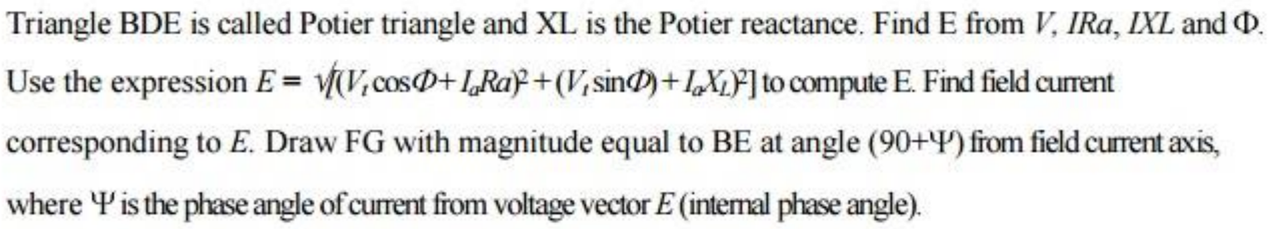


Fig: 1.21

By suitable tests plot OCC and SCC. Draw air gap line. Conduct ZPF test at full load for rated voltage and fix the point B. Draw the line BH with length equal to field current required to produce full load current on short circuit. Draw HD parallel to the air gap line so as to cut the OCC. Draw DE perpendicular to HB or parallel to voltage axis. Now, DE represents voltage drop IXL and BE represents the field current required to overcome the effect of armature reaction.



Triangle BDE is called Potier triangle and XL is the Potier reactance. Find E from *V*, *IRa*, *IXL* and Φ. Use the expression $E = \sqrt{[(V_t\cos\Phi + I_a Ra)^2 + (V_t\sin\Phi) + I_a X_L)^2]}$ to compute E. Find field current corresponding to *E*. Draw FG with magnitude equal to BE at angle (90+Ψ) from field current axis, where Ψ is the phase angle of current from voltage vector *E* (internal phase angle).

The resultant field current is given by OG. Mark this length on field current axis. From OCC find the corresponding E0. Find the regulation.

Synchronization of Generators

Often electrical generators are removed from the service and connected back to the power system during variations of the load, emergency outages, maintenance, etc.

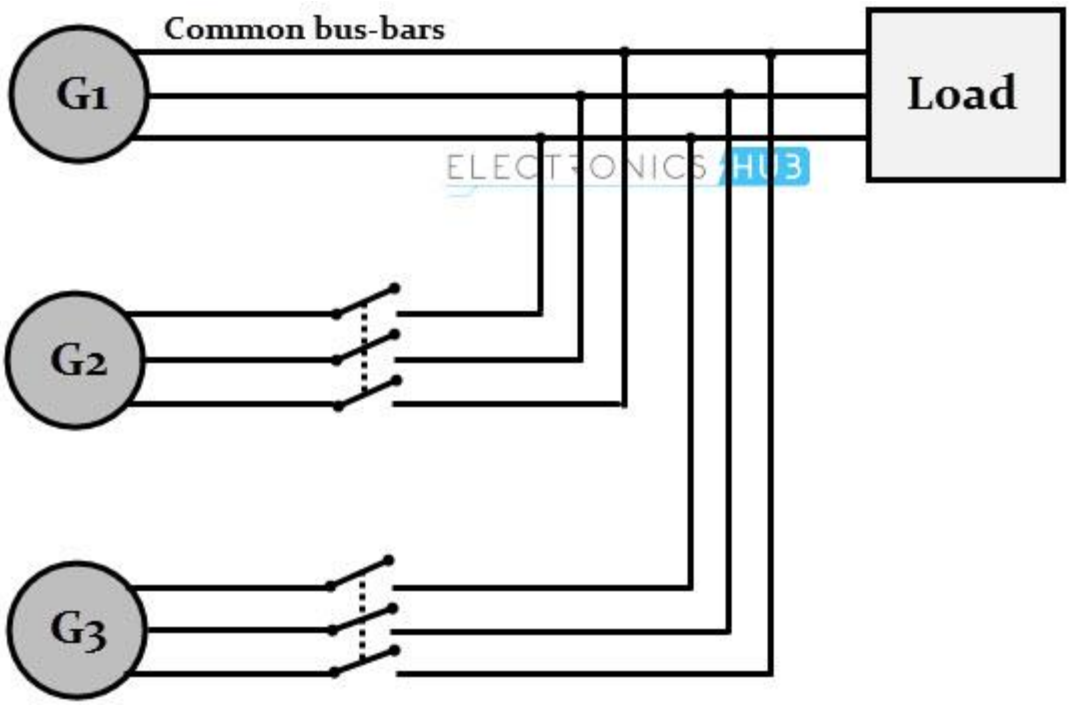
Before reconnecting the generator to the system in each time, it must be synchronized with parameters of the power system network.

An improper synchronization can affect the healthy power system and results in electrical and mechanical transients that can damage the prime mover, generator, transformers and other power system components.

What is Synchronization of Generators?

The process of matching parameters such as voltage, frequency, phase angle, phase sequence and waveform of alternator (generator) or other source with a healthy or running power system is called synchronization.

Generator cannot deliver power to electric power system unless its voltage, frequency and other parameters are exactly matched with the network. Synchronization is accomplished by controlling the exciter current and the engine speed of the generator.



The need for synchronization arrives, particularly when two or more alternators are working together to supply the power to the load. This is because electrical loads are not constant and they vary with time and hence they necessitate the interconnection of two or more alternators operating in parallel to supply larger loads.

Synchronization matches various parameters of one alternator (or generator) to another alternator or to the bus bar. The process of synchronization is also called as paralleling of alternators.

Need of Paralleling of Generators

In most commercial power plants, several small units supply the power rather than single large unit. This is called as parallel operation of generators. The reasons for preferring this practice are enumerated below.

Paralleling of Generators

i) Reliability

Several small units are more reliable than single large unit. This is because, if one alternator is failed, other alternators are still active and hence the whole system will not be shutdown.

ii) Continuity of Service

In case of periodic maintenance, break-down, or repairs of one alternator, it must be shutdown and removed from service. Since the other machines are operating in parallel, the interruption to supply the load is prevented.

iii) Load Requirements

The load requirements in the central station changes continuously. During light-load periods only one or two generators are operated to supply the load demands. During peak-load demands, other alternators are connected in parallel to meet the demand.

iv) High Efficiency

Generators run most efficiently when they are loaded at their rated values. Due to the operation of few generators at light-loads and more generators at high peak loads efficiently loads the generators.

v) Expanded Capacity

As the demand for electric power is increasing continuously, utility companies have been increasing the physical size of the generating plants by adding more alternators. So these alternators have to be connected in parallel with the existing generator equipment.

Conditions For Synchronization Or Paralleling Of Generators

There are certain requirements that must be met for successful paralleling of alternators. The following conditions must be met in order to synchronize a generator to the grid or with other generators.

i) Phase Sequence

The phase sequence of the three phases of the alternator which is being connected to the power system bus must be same as the phase sequence of the three phases of the bus bar (or electric grid). This problem comes mainly in the event of initial installation or after maintenance.

ii) Voltage Magnitude

The RMS voltage of the incoming alternator should be same as the RMS voltage of the bus bar or electric grid. If the incoming alternator voltage is more than the bus bar voltage, there will be a high reactive power that flows from the generator into the grid.

If the incoming alternator voltage is lower than the bus bar voltage, generator absorbs the high reactive power from the bus bar.

iii) Frequency

The frequency of the incoming generator must be equal to the frequency of the bus bar. Improper matching of frequency results high acceleration and deceleration in the prime mover that increases the transient torque.

iv) Phase Angle

The phase angle between the incoming generator voltage and voltage of the bus bar should be zero. This can be observed by comparing the occurrence of zero crossing or peaks of the voltage waveforms.

Procedure For Connecting Alternators In Parallel

When the above stated methods are fulfilled, the alternators are said to be in synchronism. The actual process of synchronization or paralleling generators includes the following steps.

Connecting Alternators in Parallel:

Consider that alternator-1 is supplying power to the bus bars at rated voltage and frequency.

Now, an incoming alternator-2 is to be connected in parallel with alternator-1 for the first time. By increasing the speed of the alternator, its frequency is varied and hence the speed is adjusted till it matches with bus bar frequency (or the frequency of alternator-1). Also by varying the field rheostat, the voltage of the alternator-2 is varied and hence it is adjusted till the voltage matches with bus bar voltage.

The three voltages generated by the alternator-2 must be in phase with the respective voltages of the bus bar (or alternator-1). This is achieved by maintaining the same phase sequence and frequency of alternator-2 with bus bar or alternator-1. For achieving these relationships, synchronizing lamps technique is used.

Techniques for Synchronization

There are different techniques being available for the synchronization of alternators. The primary purpose of these techniques is to check all four conditions discussed above. The common methods used for synchronizing the alternators are given below.

1. Three Dark Lamps Method
2. Two Bright, One Dark Method
3. Synchroscope Method

1. Three Dark Lamps Method

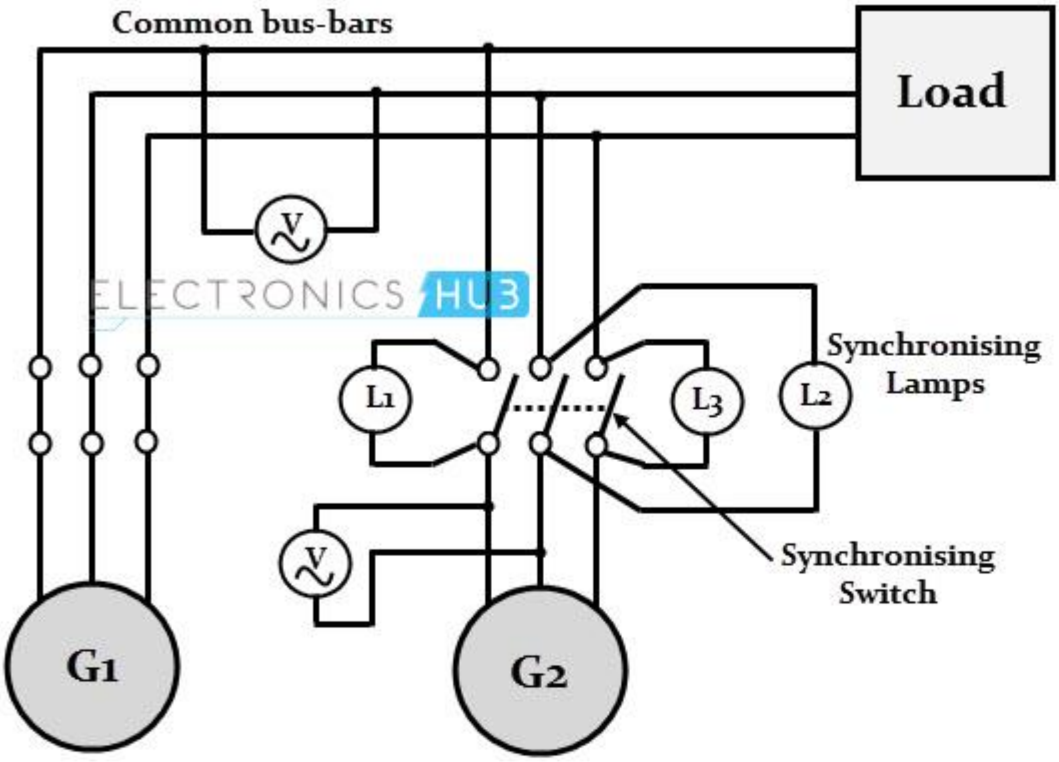
The figure below shows the circuit for bright lamp method used to synchronize the alternators. Assume that alternator is connected to the load supplying rated voltage and frequency to it. Now the alternator-2 is to be connected in parallel with alternator-1.

Three lamps (each of which is rated for alternator terminal voltage) are connected across the switches of the alternator-2. From the figure it is clear that the moment when all the conditions of parallel operation are satisfied, the lamps should be more or less dark.

To synchronize the alternator-2 with bus bar, the prime mover of the alternator-2 is driven at speed close to the synchronous speed decided by the bus bar frequency and number of poles of the alternator. Now the field current of the generator-2 is increased till voltage across the machine terminals is equal to the bus bar voltage (by observing the readings on voltmeters).

If lamps go ON and OFF concurrently , indicating that the phase sequence of alternator-2 matches with bus bar. On the other hand, if they ON and OFF one after another, it resembles the incorrect phase sequence.

By changing the connections of any two leads of alternator-2 after shutting down the machine, the phase sequence can be changed.



Depending on the frequency difference between alternator-2 voltage and bus bar voltage, ON and OFF rate of these lamps is decided. Hence, the rate of flickering has to be reduced to match the frequency. This is possible by adjusting the speed of alternator by its prime mover control.

When all these parameters are set, the lamps become dark and then the synchronizing switch can be closed to synchronize alternator-2 with alternator-1.

The main disadvantage of this method is that rate of flickering only indicates the difference between the alternator-2 and the bus bar. But the information of alternator frequency in relation to bus bar frequency is not available in this method.

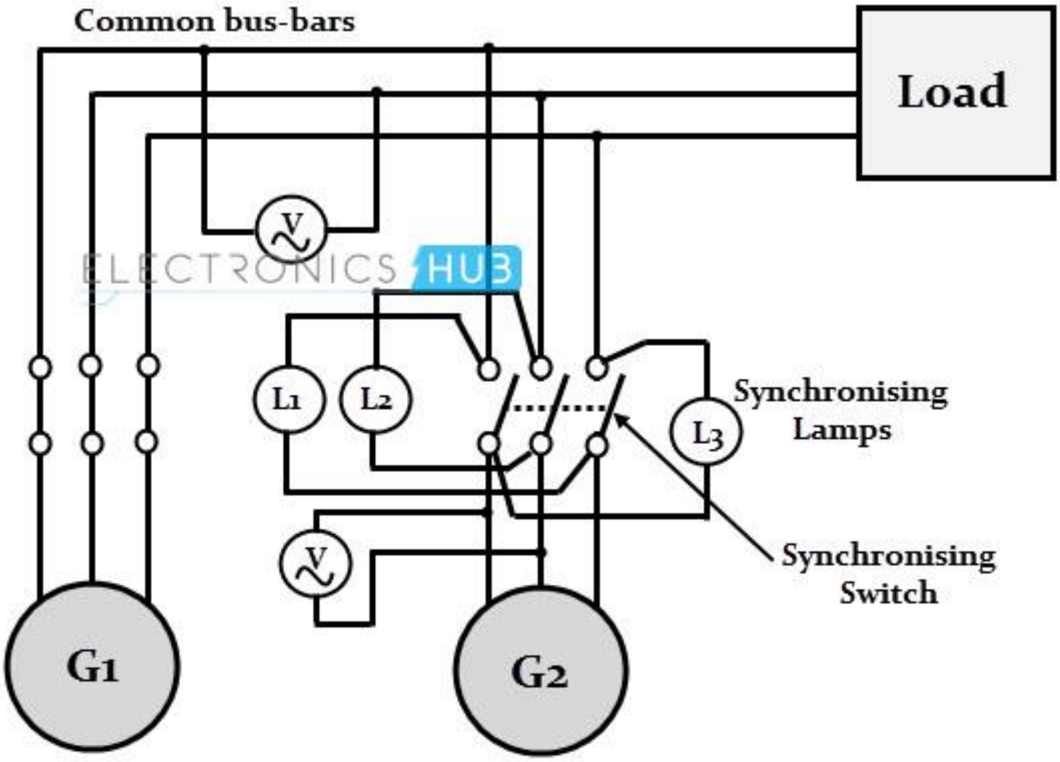
Suppose, if the bus bar frequency is 50Hz, the rate of flickering of lamps is same when the frequency of the alternator is either 51 or 49 Hz, as the difference in these two cases is 1Hz.

2. Two Bright and One Dark Lamp Method

The connections for this method are shown in figure below and it is useful in finding whether the alternator frequency is lower or higher than the bus bar frequency.

Here, the lamp L2 is connected across the pole in the middle line of synchronizing switch as similar to the dark lamp method, whereas the lamps L1 and L3 are connected in a transposed manner.

The voltage condition checking is similar to the previous method and after it, the lamps glow bright and dark one after another. The lower or higher value of alternator frequency in comparison with bus bar frequency is determined by the sequence in which the lamps become dark and bright.



The sequence of becoming bright and dark L1- L2 – L3 indicates that the incoming generator frequency is higher than the bus bar frequency. Hence, the alternator speed has to be reduced by prime mover control till the flickering rate is brought down to a small.

On the other hand, the sequence flickering L1- L3 – L2 indicates that incoming alternator frequency is less than that of bus bar.

Hence, the speed of the alternator is increased by the prime mover till the rate of flickering is brought down to as small as possible. The synchronizing switch is then closed at the instant when lamps L1 and L3 are equally bright and lamp L2 is dark.

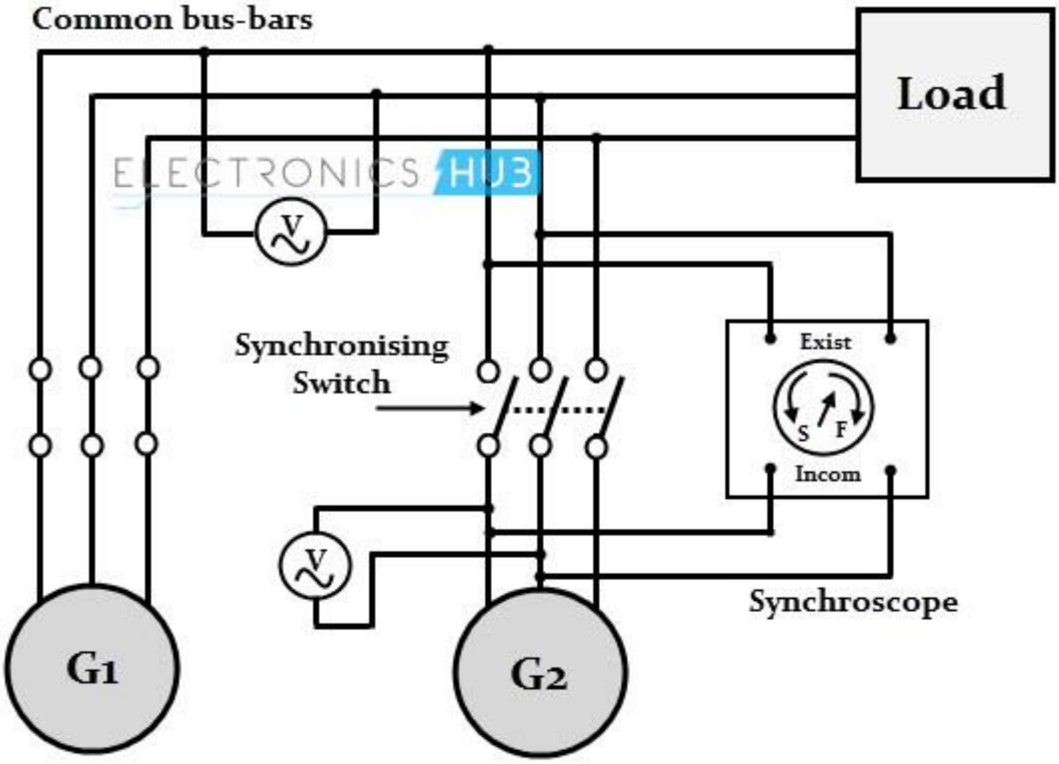
The disadvantage of this method is that the correctness of phase sequence cannot be checked. However, this requirement is unnecessary for permanently connected alternators where checking of phase sequence is enough to be carried out for the first time of operation alone.

Synchroscope Method.

It is similar to the two bright and one dark lamp method and indicates whether the alternator frequency is higher or lower than the bus bar frequency. A synchroscope is used for better accuracy of synchronization and it consists of two pairs of terminals.

One pair of terminals marked as ‘existing’ has to be connected across the bus bar terminals or to the existing alternator and other pair of terminals marked as ‘incoming’ has to be connected across the terminals of incoming alternator.

The synchroscope has circular dial over which a pointer is hinged that is capable of rotating in clockwise and anticlockwise directions.



After the voltage condition is checked, the operator has to check the synchroscope. The rate at which the pointer rotates indicates the difference of frequency between the incoming alternator and the bus bar.

Also, the direction to which the pointer rotates (to either fast or slow) gives the information, whether the incoming alternator frequency is higher or lower than the bus bar frequency and hence the pointer moves either fast or slow.

The appropriate correction has to be made to control the speed of the alternator so as to bring the rate of rotation of pointer as small as possible. Therefore, synchroscope along with voltmeters are enough for synchronization process. However, in most of the cases a set of lights along with synchroscope is used as a double-check system.

These are the methods of synchronizing the generators. This process must be done carefully to prevent the disturbances in the power system as well as to avoid a serious damage to the machine. Only three lamps methods are not preferred today due to less accuracy and manual operation.

These processes need a skilled and experienced person to handle the equipment while synchronizing. In most cases synchroscope method with set of lamps is used as mentioned above.
Modern synchronization equipments automate the whole synchronization process with the use of microprocessor based systems that avoids manual lamps and synchroscope observations. These methods are easier to manage and more reliable.

Two Reaction Theory

Two Reaction Theory was proposed by Andre Blondel. The theory proposes to resolve the given armature MMFs into two mutually perpendicular components, with one located along the axis of the rotor of the salient pole. It is known as the direct axis or d axis component. The other component is located perpendicular to the axis of the rotor salient pole. It is known as the quadrature axis or q axis component.

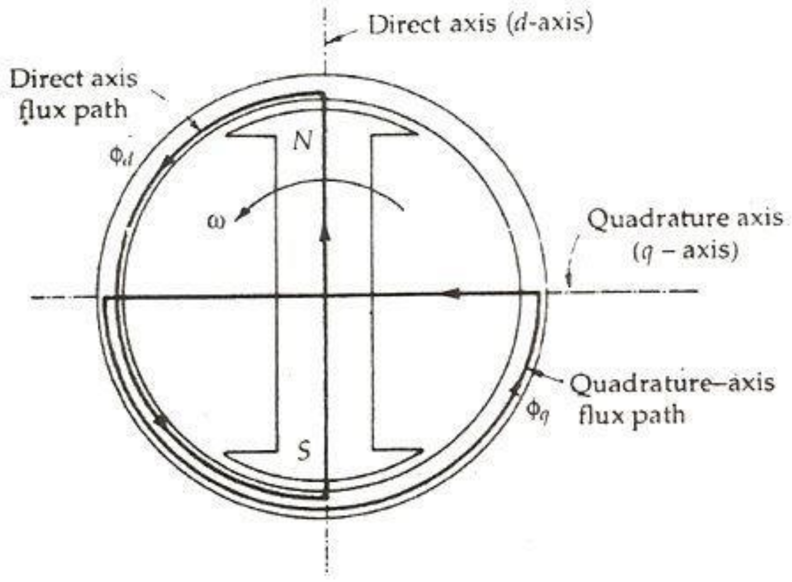
The d axis component of the armature MMF F_a is denoted by F_d and the q axis component by F_q. The component F_d is either magnetizing or demagnetizing. The component F_q results in a cross-magnetizing effect. If Ψ is the angle between the armature current I_a and the excitation voltage E_f and F_a is the amplitude of the armature MMF, then

$$F_d = F_a \sin \Psi \qquad \text{and}$$

$$F_q = F_a \cos \Psi$$

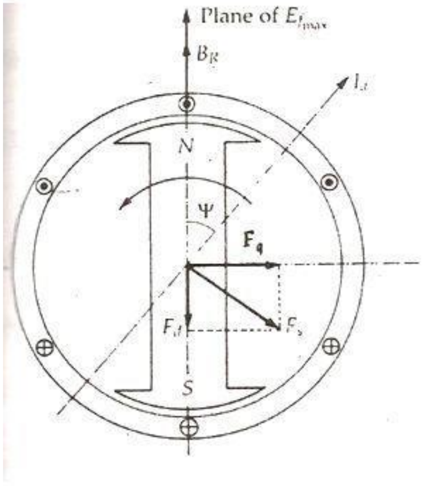
Salient Pole Synchronous Machine Two Rection Theory

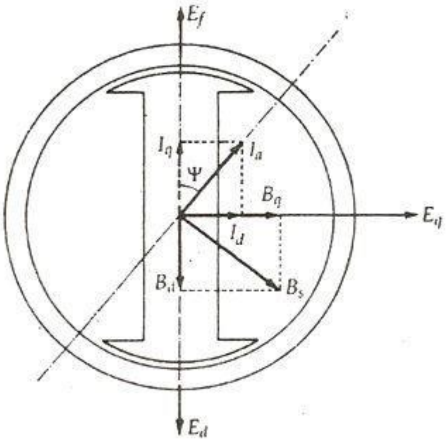
In the cylindrical rotor synchronous machine, the air gap is uniform. The pole structure of the rotor of a salient pole machine makes the air gap highly non-uniform. Consider a 2 pole, salient pole rotor rotating in the anticlockwise direction within a 2 pole stator as shown in the figure below.



The axis along the axis of the rotor is called the direct or the d axis. The axis perpendicular to d axis is known as the quadrature or q axis. The direct axis flux path involves two small air gaps and is the path of the minimum reluctance. The path shown in the above figure by ϕ_q has two large air gaps and is the path of the maximum reluctance.

The rotor flux B_R is shown vertically upwards as shown in the figure below.





The rotor flux induces a voltage E_f in the stator. The stator armature current I_a will flow through the synchronous motor when a lagging power factor load is connected it. This stator armature current I_a lags behind the generated voltage E_f by an angle Ψ.

The armature current produces stator magneto motive force F_s. This MMF lags behind I_a by angle 90 degrees. The MMF F_S produces stator magnetic field B_S long the direction of Fs. The stator MMF is resolved into two components, namely the direct axis component F_d and the quadrature axis component F_q.

If,

ϕ_d is the direct axis flux

Φ_q is the quadrature axis flux

R_d is the reluctance of the direct axis flux path

$$\varphi_d = \frac{F_d}{R_d}$$

$$\varphi_q = \frac{F_q}{R_q}$$

Therefore

As, $R_d < R_q$, the direct axis component of MMF F_d produces more flux than the quadrature axis component of the MMF. The fluxes of the direct and quadrature axis produce a voltage in the windings of the stator by armature reaction.

Let,

E_{ad} be the direct axis component of the armature reaction voltage.

E_{aq} be the quadrature axis component of the armature reaction voltage.

Since each armature reaction voltage is directly proportional to its stator current and lags behind by 90 degrees angles. Therefore, armature reaction voltages can be written as shown below.

$$E_{ad} = -j\,X_{ad}\,I_d \quad \dots\dots\dots (1)$$

$$E_{aq} = -j\,X_{aq}\,I_q \quad \dots\dots\dots (2)$$

Where,

X_{ad} is the armature reaction reactance in the direct axis per phase.

X_{aq} is the armature reaction reactance in the quadrature axis per phase.

The value of X_{ad} is always greater than X_{aq}. As the EMF induced by a given MMF acting on the direct axis is smaller than for the quadrature axis due to its higher reluctance.

The total voltage induced in the stator is the sum of EMF induced by the field excitation. The equations are written as follows :-

$$E' = E_f + E_{ad} + E_{aq} \quad \dots\dots\dots (3) \quad \text{or}$$

$$E' = E_f - j\,X_{ad}I_d - j\,X_{aq}I_q \quad \dots\dots. (4)$$

The voltage E’ is equal to the sum of the terminal voltage V and the voltage drops in the resistance and leakage reactance of the armature. The equation is written as

$$E' = V + R_a I_a + j X_l I_a \quad \dots \dots (5)$$

The armature current is divided into two components; one is the phase with the excitation voltage E_f and the other is in phase quadrature to it. If

I_q is the axis component of I_a in phase with E_f.

I_d is the d axis I_a lagging E_f by 90 degrees.

Therefore,

$$I_a = I_d + I_q \quad \dots \dots (6)$$

Combining the equation (4) and (5) we get

$$E_f = V + R_a I_a + jX_l I_a + jX_{ad} I_d + jX_{aq} I_q \dots \dots \dots (7)$$

Combining the equation (6) and (7) we get

$$E_f = V + R_a\left(I_d + I_q\right) + j X_l\left(I_d + I_q\right) + jX_{ad} I_d + jX_{aq} I_q \dots \dots \dots (8)$$

$$E_f = V + R_a\left(I_d + I_q\right) + j(X_l + X_{ad})I_d + j\left(X_l + X_{aq}\right) I_q \quad \dots \dots (9)$$

Let,

$$X_d \triangleq X_l + X_{ad} \dots \dots \dots (10)$$

$$X_q \triangleq X_l + X_{aq} \dots \dots \dots (11)$$

The reactance X_d is called the **direct axis synchronous reactance**, and the reactance X_q is called the **quadrature axis synchronous reactance.**

Combining the equations (9) (10) and (11), we get the equations shown below.

$$E_f = V + R_a I_d + R_a I_q + jX_d I_d + jX_q I_q \dots \dots \dots (12) \text{ or}$$

$$E_f = V + R_a I_a + jX_d I_d + jX_q I_q \dots \dots \dots (13)$$

The equation (12) shown above is the final voltage equation for a salient pole synchronous generator.

Synchronous Generators:Parallel Operation Of Ac Generators

Parallel Operation Of Ac Generators

In most generator applications, there is more than one generator operating in parallel to supply power to various loads. The North American grid is an extreme example of a situation where thousands of generators share the load on the system.

The major advantages for operating synchronous generators in parallel are as follows:

1. The reliability of the power system increases when many generators are operating in parallel, because the failure of any one of them does not cause a total power loss to the loads.
2. When many generators operate in parallel, one or more of them can be taken out when failures occur in power plants or for preventive maintenance.
3. If one generator is used, it cannot operate near full load (because the loads are changing), then it will be inefficient. When several machines are operating in parallel, it is possible to operate only a fraction of them. The ones that are operating will be more efficient because they are near full load.

The Conditions Required for Paralleling

Figure 12.19 illustrates a synchronous generator G1 supplying power to a load with another generator G2 that is about to be paralleled with G1 by closing the switch S1. If the switch is closed at some arbitrary moment, the generators could be severely damaged and the load may lose power. If the voltages are different in the conductors being tied together, there will be very large current flow when the switch is closed.

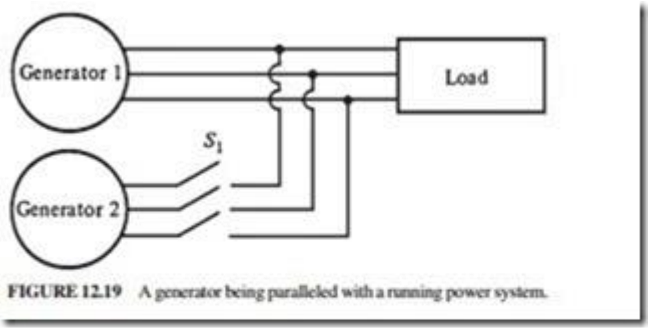


FIGURE 12.19 A generator being paralleled with a running power system.

This problem can be avoided by ensuring that each of the three phases has the same voltage magnitude and phase angle as the conductor to which it is connected. To ensure this match, these paralleling conditions must be met:

1. The two generators must have the same rms line voltages.
2. The phase sequence must be the same in the two generators.
3. The two a phases must have the same phase angles.

4. The frequency of the oncoming generator must be slightly higher than the frequency of the running system.

If the sequence in which the phase voltages peak in the two generators is different (Fig. 12.20a), then two pairs of voltages are 120° out of phase, and only one pair of voltages (the a phases) is in phase. If the generators are connected in this manner, large currents will flow in phases b and c, causing damage to both machines.

The phase sequence problem can be corrected by swapping the connections on any two of the three phases on one of the generators.

If the frequencies of the power supplied by the two generators are not almost equal when they are connected together, large power transients will occur until the generators stabilize at a common frequency. The frequencies of the two generators must differ by a small amount so that the phase angles of the oncoming generator will change slowly relative to the phase angles of the running system. The angles between the voltages can be observed, and switch S1 can be closed when the systems are exactly in phase.

The General Procedure for Paralleling Generators

If generator G2 is to be connected to the running system (Fig. 12.20), the following steps should be taken to accomplish paralleling:

1. The terminal voltage of the oncoming generator should be adjusted by changing the field current until it is equal to the line voltage of the running system.

2. The phase sequences of the oncoming generator and of the running system should be the same. The phase sequence can be checked by using the following methods:

a. A small induction motor can be connected alternately to the terminals of each of the two generators. If the motor rotates in the same direction each time, then the phase sequences of both generators are the same. If the phase sequences are different, the motors will rotate in opposite directions. In this case, two of the conductors on the incoming generator must be reversed.

b. Figure 12.20b illustrates three lightbulbs connected across the terminals of the switch connecting the generator to the system. When the phase changes between the two systems, the lightbulbs become bright when the phase difference is large and dim when the phase difference is small. When the systems have the same phase sequence, all three bulbs become bright and dim simultaneously. If the systems have opposite phase sequence, the bulbs get bright in succession.

The frequency of the oncoming generator should be slightly higher than the frequency of the running system. A frequency meter is used until the frequencies are close; then changes in phase between the the generator and the system are observed.

The frequency of the oncoming generator is adjusted to a slightly higher frequency to ensure that when it is connected, it will come on-line supplying power as a generator, instead of consuming it as a motor.

Once the frequencies are almost equal, the voltages in the two systems will change phase relative to each other very slowly. This change in phase is observed, and the switch connecting the two systems together is closed when the phase angles are equal (Fig. 12.21). A confirmation that the two systems are in phase can be achieved by watching the three light bulbs. The systems are in phase when the three light bulbs all go out (because the voltage difference across them is zero).

This simple scheme is useful, but it is not very accurate. A synchroscope is more accurate. It is a meter that measures the difference in phase angle between the a phases of the two systems (Fig. 12.22). The phase difference between the two a phases is shown by the dial. When the systems are in phase (0° phase difference), the dial is at the top. When they are 180° out of phase, the dial is at the bottom.

The phase angle on the meter changes slowly because the frequencies of the two systems are slightly different. Since the oncoming generator frequency is slightly higher than the system frequency, the synchroscope needle rotates clockwise because the phase angle advances. If the oncoming generator frequency is lower than the system frequency, the

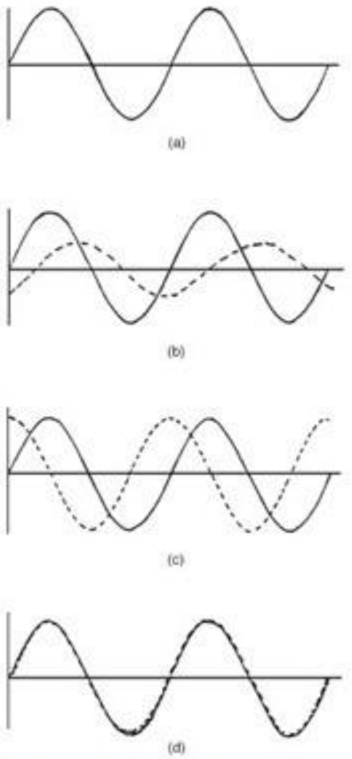


FIGURE 12.21 Steps taken to synchronize an incoming ac generator to the supply system. (*a*) Existing system voltage wave. (One phase only shown.) (*b*) Machine voltage wave shown dotted. Out of phase and frequency. Being built up to equal the system max. volts by adjustment of field rheostat. (*c*) Machine voltage now equal to system. Voltage waves out of phase but frequency being increased by increasing speed of prime mover. (*d*) Machine voltage now equal to system, in phase and with equal frequency. Synchroscope shows 12 o'clock. Switch can now be closed.

(c) Machine voltage now equal to system. Voltage waves out of phase but frequency being increased by increasing speed of prime mover. (d) Machine voltage now equal to system, in phase and with equal frequency. Synchroscope shows 12 o’clock. Switch can now be closed.

needle rotates counterclockwise. When the needle of the synchroscope stops in the vertical position, the voltages are in phase and the switch can be closed to connect the systems.

However, the synchroscope provides the relationship for only one phase. It does not provide information about the phase sequence.

The whole process of paralleling large generators to the line is done by a computer. For small generators, the operator performs the paralleling steps.

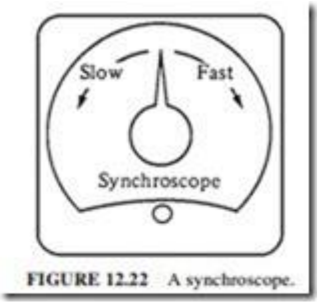


FIGURE 12.22 A synchroscope.

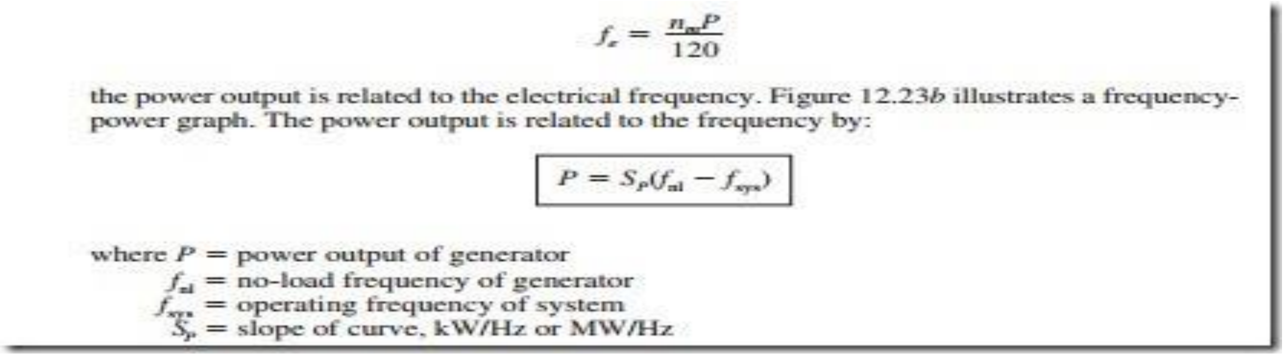
Frequency-Power and Voltage-Reactive Power Characteristics of a Synchronous Generator

The mechanical source of power for the generator is a prime mover such as diesel engines or steam, gas, water, and wind turbines. All prime movers behave in a similar fashion. As the power drawn from them increases, the rotational speed decreases. In general, this decrease in speed is nonlinear. However, the governor makes this decrease in speed linear with increasing power demand.

$$\boxed{\mathrm{SD} = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100\%}$$

Thus, the governing system has a slight speed drooping characteristic with increasing load. The speed droop (SD) of a prime mover is defined by where nnl is the no-load speed of the prime mover and nfl is the full-load speed of the prime mover. The speed droop of most generators is usually 2 to 4 percent. In addition, most governors have a set-point adjustment to allow the no-load speed of the turbine to be varied. A typical speed-power curve is shown in Fig. 12.23.

Since the electrical frequency is related to the shaft speed and the number of poles by



$$f_e = \frac{n_m P}{120}$$

the power output is related to the electrical frequency. Figure 12.23b illustrates a frequency-power graph. The power output is related to the frequency by:

$$\boxed{P = S_P(f_{nl} - f_{sys})}$$

where P = power output of generator
f_{nl} = no-load frequency of generator
f_{sys} = operating frequency of system
S_P = slope of curve, kW/Hz or MW/Hz

The reactive power Q has a similar relationship with the terminal voltage VT . As pre- viously described, the terminal voltage drops when a lagging load is added to a synchronous generator. The terminal voltage increases when a leading load is added to a synchro- nous generator. Figure 12.24 illustrates a plot of terminal voltage versus reactive power.

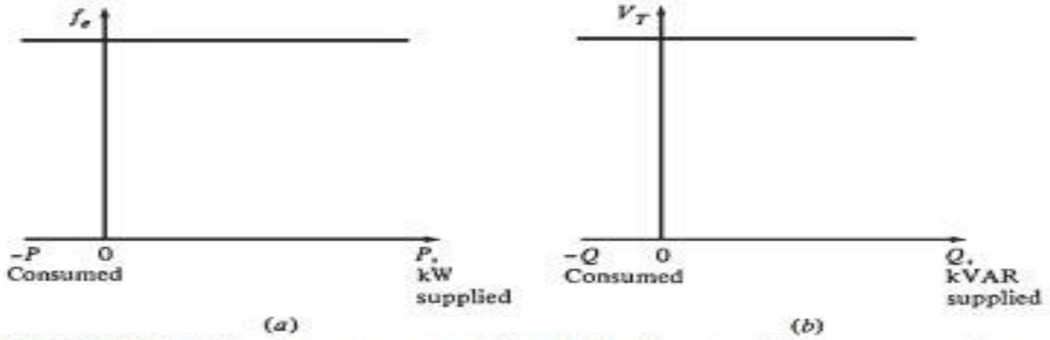


FIGURE 12.25 The frequency-power and terminal voltage-reactive power curves for an infinite bus.

This plot has a drooping characteristic that is not generally linear, but most generator voltage regulators have a feature to make this characteristic linear.

When the no-load terminal voltage set point on the voltage regulator is changed, the curve can slide up and down.

The frequency-power and terminal voltage-reactive power characteristics play important roles in parallel operation of synchronous generators. When a single generator is operating alone, the real power P and reactive power Q are equal to the amounts demanded by the loads.

The generator’s controls cannot control the real and reactive power supplied. Therefore, for a given real power, the generator’s operating frequency fe is controlled by the governor set points, and for a given reactive power, the generator’s terminal voltage VT is controlled by the field current.

MODULE V
SYNCHRONOUS MOTORS

Synchronous motor is one of the most efficient motors. The ability to control their power factor makes it very demandable especially for low speed drives. This will discuss Synchronous motor, its construction, working principle, types, characteristics, starting methods, applications, model/ phasor diagram, advantages and disadvantages.

What is Synchronous Motor

A synchronous motor is an AC motor wherein, at steady state, the rotation of the shaft is synchronized with the frequency of the supplied current; the rotation period is exactly equal to an integral number of AC cycles.

Fig. 1 – Synchronous Motor

These motors contain multi-phase AC electromagnets on the stator of the motor that create a magnetic field that rotates in time with the oscillations of the line current. A synchronous-motor is doubly fed if it is supplied with independent excited multi-phase AC electromagnets on both the rotor and stator.

Construction Of Synchronous Motor

The structure is same as of other motors. Stator and rotor are the main parts of a synchronous motor while a frame is the cover and both stator and rotor make up the electric and magnetic circuitry of the Synchronous motors. The main components of the motor are:

1) Stator
2) Rotor
3) Exciter
4) Frame

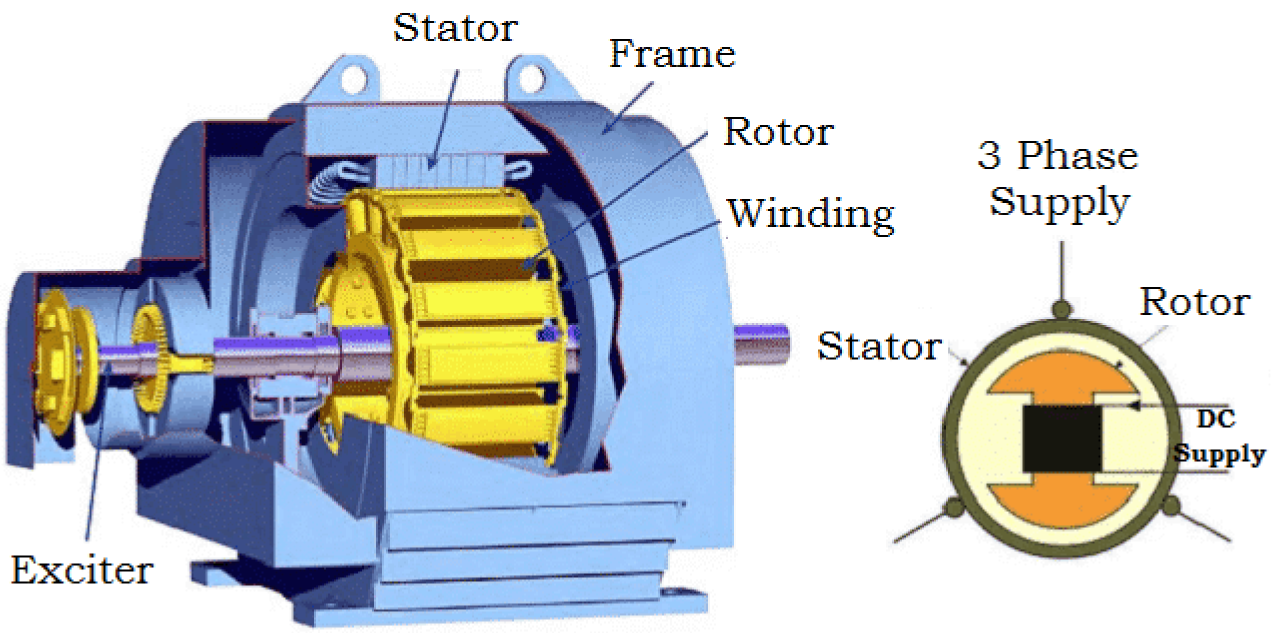
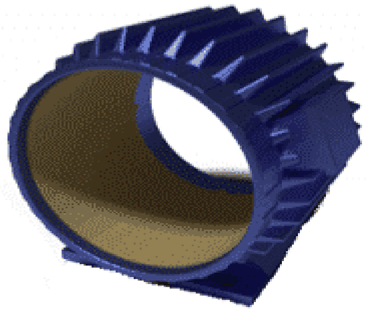


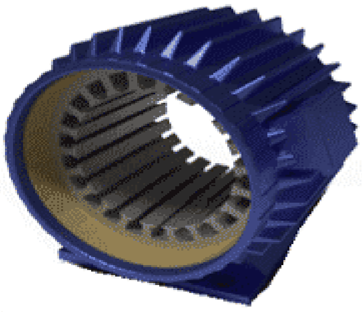
Fig. 2 – Components of Synchronous Motor

1) Stator

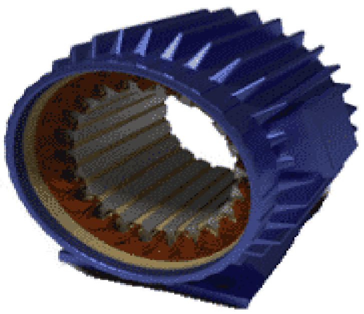
Stator is the stationary part of the motor. It has a cylindrical frame which has slots to carry winding circuitry. The Stator consists of the core, which is generally made up of steel. This core is insulated to prevent the flow of eddy currents.



Stator Frame



Stator Core



Stator Winding

Fig. 3 – Components of Stator

The winding circuit of the stator is called Stator Winding. It is supplied 3 phase AC power.

2) Rotor

Rotor is the rotating part that rotates exactly at the same speed as the stator magnetic field. It is excited by a DC source.

The rotor consists of a number of poles, which depends on the speed and frequency of the machine. The relation between the pole, speed and frequency is defined as

$$N = 120 \times \frac{f}{p}$$

Where,

N = Speed of Motor in rpm

f = frequency, and

p = No. of poles

Types of Rotor Construction in Synchronous Motor

There are two types of rotor constructions in Synchronous Motors. They are:

i) Salient Pole Rotors

ii) Non-Salient Pole Rotors

i) Salient Pole Rotors

In Salient Pole Rotors, the poles protrude from the rotor surface.

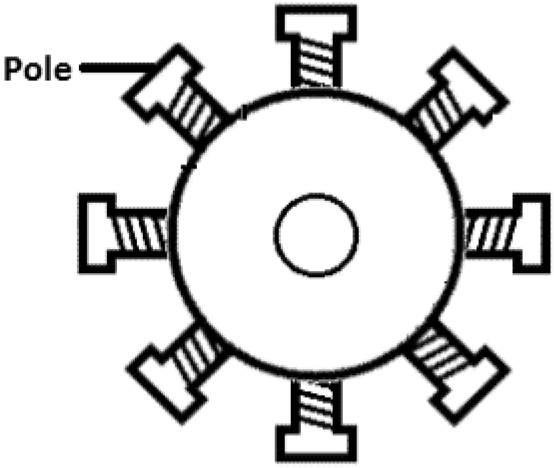


Fig. 4 – Salient Pole Rotor

ii) Non-Salient Pole Rotors

In Non-Salient Pole Rotors, winding are placed in slots machined rotors.

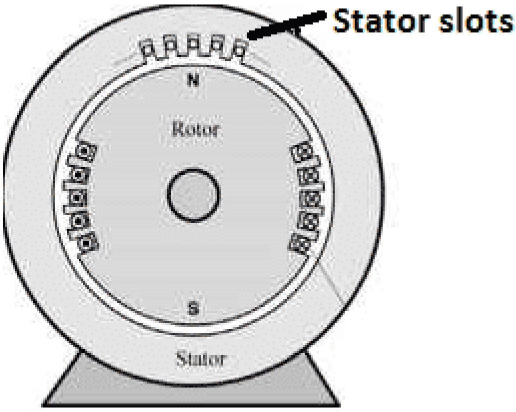


Fig. 5 – Non-Salient Pole Rotor

3) Exciter

It is a small generator placed in the rotor, which provides excitation power for excitation. It consists of a field winding and armature winding. The field winding is placed in stator and the armature winding is placed in the rotor of the machine.

4) Frame

It protects the motor and covers the whole assembly.

Working Principle of Synchronous Motor

The operation of a synchronous motors is that the rotor follows the rotating magnetic field of a stator and rotates at a speed approaching it. The rotor winding is excited by a DC source and the stator winding is excited by AC source.

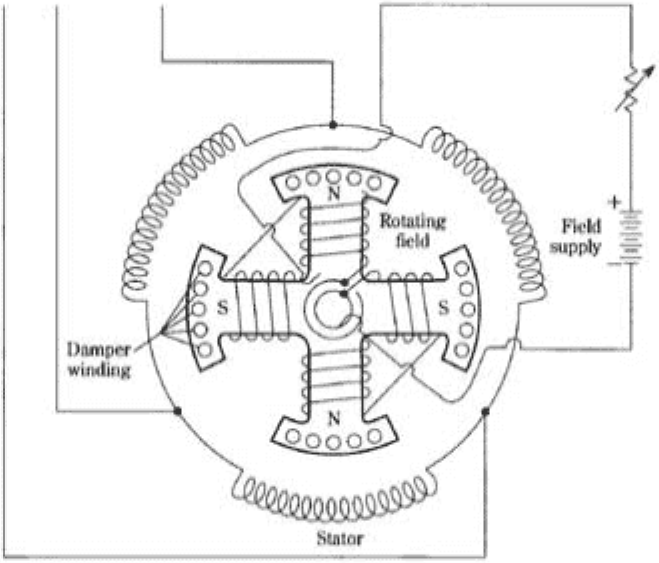


Fig. 6 – Synchronous Motor Working Principle

Salient points regarding the working principle of Synchronous Motor are:

Due to 3 phase AC, a 3 phase rotating magnetic field is produced by stator winding. Rotor winding produces a constant magnetic field. At some rotations, the poles of two magnetic fields attract each other while at some instant, they repel each other.

The rotor will not start to rotate due to its inertia. So an external source will provide initial rotation. Once the rotor starts moving at the synchronous speed, the external source is shut off. The magnetic field of a rotor is not produced by the magnetic field of the rotor but through induction. Hence, the air gap between rotor and stator is not kept very small.

Types Of Synchronous Motor

Synchronous motors can be classified into two types based on how the rotor is magnetized.

i) Non-Excited Synchronous Motors

ii) Direct Current (DC) Excited Synchronous Motors

i) Non Excited Synchronous Motor

The rotor is made up of steel. At synchronous speed, it rotates with the rotating magnetic field of the stator, so it has an almost-constant magnetic field through it. The rotor is made of high-retentively steel such as cobalt steel.

Non-Excited Synchronous Motors are available in three designs:

a) Hysteresis Synchronous Motors

b) Reluctance Synchronous Motors

c) Permanent Magnet Synchronous Motors

a) Hysteresis Synchronous Motors

Hysteresis motors are single phase motors where the rotor is made of ferromagnetic material. The rotors have high hysteresis loss property. They are made up of Chrome, Cobalt Steel or Alnico.

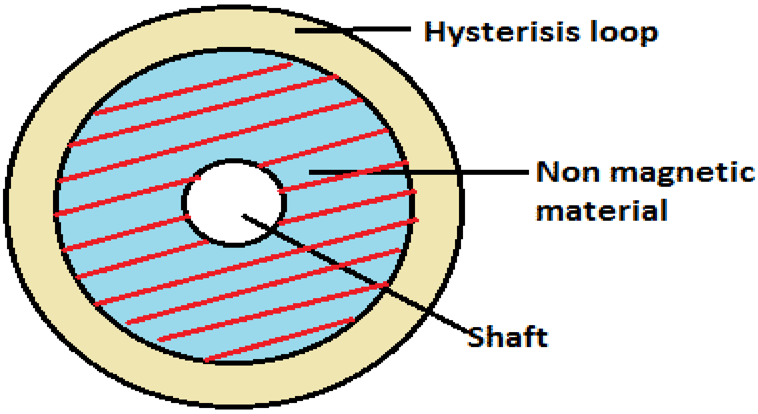


Fig. 7 – Hysteresis Synchronous Motor

They are self-starting and do not need additional winding. This has a wide hysteresis loop which means once it is magnetized in a given direction; it requires a large reverse magnetic field to reverse the magnetization.

b) Reluctance Synchronous Motors

Reluctance is always minimum when a piece of iron rotates to complete a magnetic flux path. The reluctance increases with the angle between them when the poles are aligned with the magnetic field of the stator. This will create a torque pulling the rotor into alignment with the pole near to the stator field.

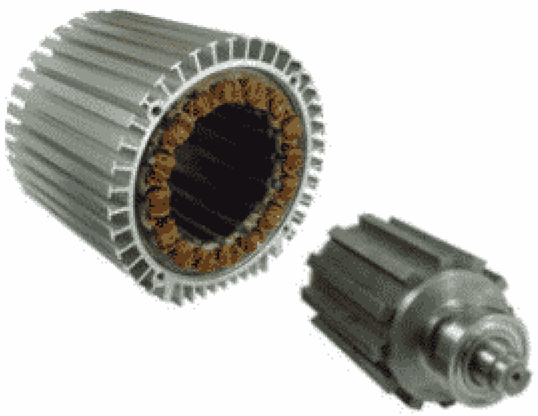


Fig. 8 – Reluctance Synchronous Motor

The rotor poles generally have squirrel-cage winding embedded, to provide torque below synchronous speed to start the motor.

c) Permanent Magnet Synchronous Motors

A permanent Magnet Motor uses permanent magnets in the steel rotor to create a constant magnetic flux. The rotor locks in when the speed is near synchronous speed.

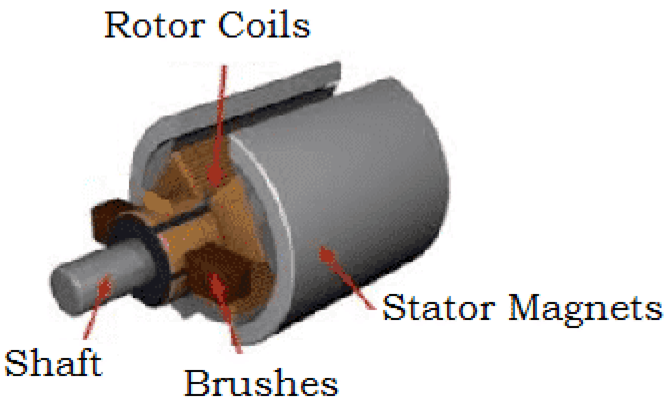


Fig. 9 – Permanent Magnet Synchronous Motor

The stator carries winding which are connected to an AC supply to produce a rotating magnetic field. Permanent magnet motors are similar to brushless DC motors.

ii) Direct Current (DC) Excited Synchronous Motor

Direct Current (DC) Excited Synchronous Motor requires DC supply to the rotor to generate a magnetic field. It has both stator winding as well as rotor winding. The direct current can be supplied from a separate DC source or from a DC generator connected to the motor shaft.

Characteristics of Synchronous Motor:

Some of the key characteristics of a synchronous motor which differentiates it from other motors are as follows:

Speed:

Speed of ranges from 150 rpm to 1800 rpm. The speed is synchronous and does not depend on load conditions. Speed always remain constant from no load to full load.

The relation between the pole, speed, and frequency is defined as

$$N = 120 \text{ x } \frac{f}{p}$$

Where,

N = Speed of Motor in rpm

f = frequency, and

p = No. of poles

Starting Torque:

External force is required to start the synchronous motor as it has no starting torque.

Rating:

The power rating of synchronous motors ranges between 150kW to 15MW.

Efficiency:

The Synchronous Motors are highly efficient machines and their efficiency is much greater than induction motors.

Maintenance:

The Synchronous motors use brushless Exciter which decreases the maintenance problem.

Power Factor Correction:

These motors have high power factor correction, Hence they are used in areas where power factor correction is needed.

Starting Methods of Synchronous Motor:

As we all know that Synchronous motors cannot self-start as it has no starting torque. Therefore different ways are used to start the motor. External force is used at start for bringing up the speed up to synchronous speed. The three main ways are:

1) Reduce frequency of stator to a safe starting level.
2) Use external prime mover.
3) Use of damper winding.

Model Diagram and Phasor Diagram of Synchronous Motor

Field structure is stimulated by direct current in synchronous motor. Due to the rotating magnetic field, the voltage induced in the stator winding and this voltage is called counter emf (E).

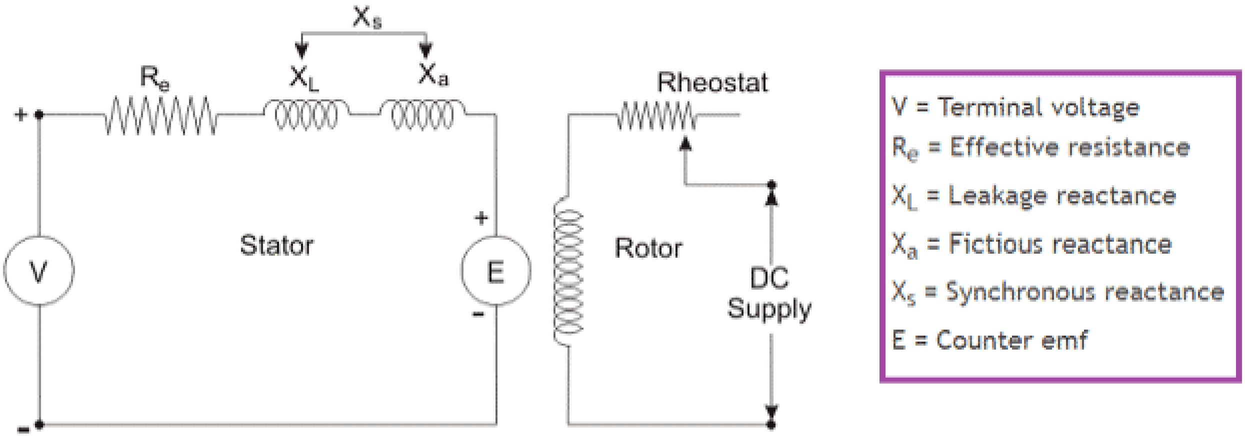


Fig. 10 – Model Diagram of Synchronous Motor

The effect of armature reaction is substituted by Fictitious Reactance (Xa). When Xa is combined with the leakage reactance of the armature it gives Synchronous Reactance (Xs). When Xs is combined with the Armature Effective Resistance (Re), it gives the Synchronous Impedance (Zs).

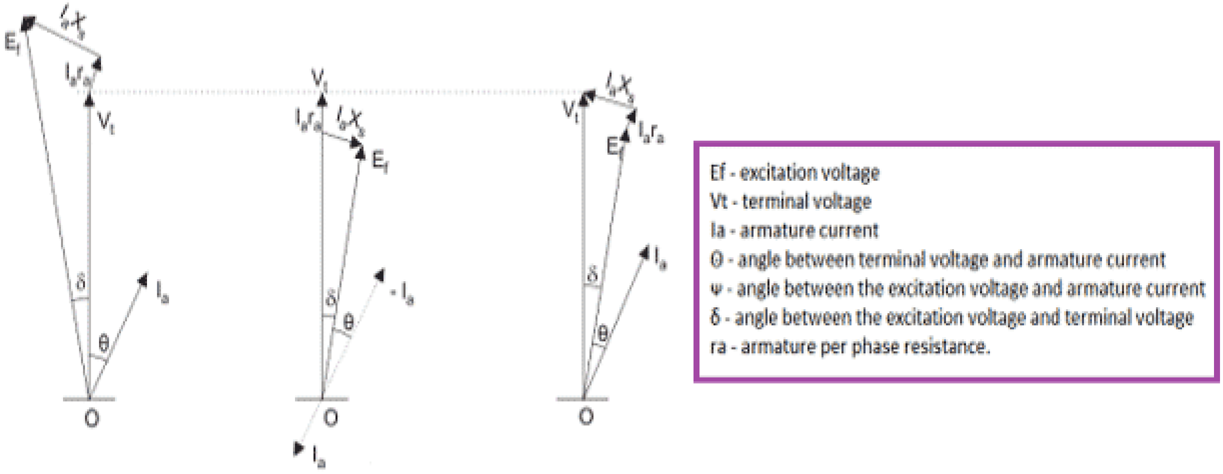


Fig. 11 – Phasor Diagram of Synchronous Motor

In order to draw the phasor diagram, Vt is taken as the reference phasor and below points are to be followed:

1) If a machine works as a asynchronous motor then the direction of armature current will be opposite to that of the excitation emf.
2) Phasor excitation emf always lags phasor terminal voltage.

Application Areas of Synchronous Motor

The application areas of Synchronous motor includes:

1) The basic use of a synchronous motor is “power factor correction” which means to increase the power factor of a system.
2) Synchronous motors are used in voltage regulation
3) Synchronous motors are generally used for low speed, high power loads.
4) Synchronous motors are generally used in air and gas compressors and vacuum pumps.
5) Synchronous motors also find their application in crushers, mills and grinders.
6) They are also used in exhausters, fans, and blowers.

Advantages of Synchronous Motor

The advantages of Synchronous motor includes:

1) The advantage of using synchronous motor is the ability to control the power factor. An over excited synchronous-motor has leading power factor and is operated in parallel to induction motors thereby improving the system power factor.
2) Speed remains constant irrespective of the loads in synchronous motors. This quality helps in industrial machines where constant speed is required irrespective of the load.
3) Synchronous motors are built with wider air gaps than induction motors which make them mechanically more stable.
4) Electro-magnetic power varies linearly with the voltage in synchronous motors.
5) Synchronous motors usually operate with higher efficiencies (more than 90%) especially in low speed compared to induction motors.

Disadvantages of Synchronous Motor

The disadvantages of Synchronous motor includes:

1) Synchronous motors require dc excitation which is supplied from external sources.
2) These motors are not self-starting motors and need some external arrangement for its starting and synchronizing.
3) The cost per kW output is commonly higher than that of induction motors.

4) Unless the incoming supply frequency is adjusted, there is no possible way to adjust the speed.
5) They cannot be started on load because its starting torque is zero.
6) Collector rings and brushes are required which results in high maintenance cost.
7) Synchronous motors cannot be useful for applications requiring frequent starting of machines.

Power Flow Diagram & Power Developed by Synchronous Motor

The phasor diagram of a synchronous motor is shown below. From the phasor diagram,

let,

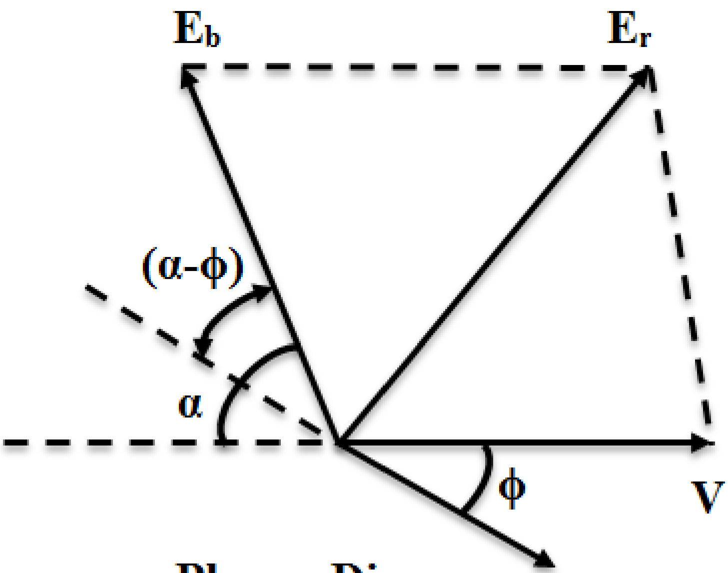
V = Supply voltage / phase

I_a = Armature current / phase

R_a = Armature resistance / phase

α = Load angle

φ = Power factor angle



Phsaor Diagram

Input Power to Motor :

Motor input power per phase is V I_a Cos φ. Now, the total input power for 3-φ star-connected motor is,

P = $\sqrt{3}\ V_L\ I_L$ Cos φ

= 3 $V_{ph}\ I_{ph}$ Cos φ

Where,

V_L and I_L are line values.

V_{ph} and I_{ph} are phase values.

Power Developed by Motor :

The mechanical power developed / phase is,

P_m = Back emf * Armature current * Cosine of the angle between E_b and I_a

$= E_b I_a \cos(\alpha - \varphi)$ for lagging p.f

$= E_b I_a \cos(\alpha + \varphi)$ for leading p.f

The copper loss in a **synchronous motor** takes place in the armature windings. Therefore,

Armature copper loss/phase=Ia2 Ra

Total copper loss=$3I^2$aRa

By subtracting the **copper loss** from the power input, we obtain the mechanical power developed by a synchronous motor as,

$P_m = P - P_{cu}$

For three-phase,

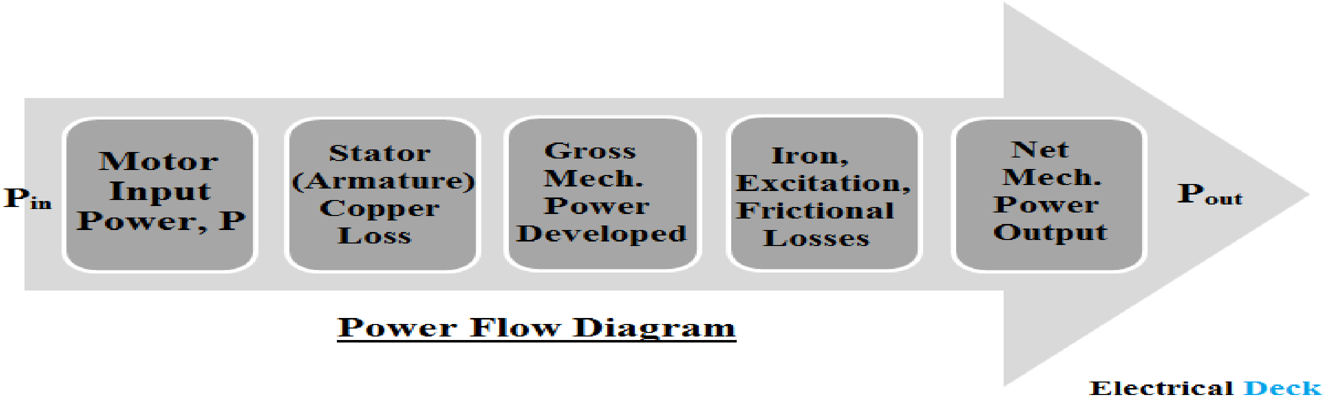
$P_m = \sqrt{3}\, I_L I_L \cos\varphi - 3 I_a^2 R_a$

Power Output of the Motor :

To obtain the power output we subtract the iron, friction, and excitation losses from the power developed.

Therefore, Net output power, $P_{out} = P_m$ - iron, friction, and excitation losses.

The above two stages can be shown diagrammatically called as Power Flow Diagram of a Synchronous Motor



Power Flow Diagram

The power developed in a synchronous motor as follows.

Motor Input Power, P
Stator (Armature) copper loss P_{cu}

Mechanical power developed, P_m

Iron, friction, and excitation losses

Output power, P_{out}

Net Power Developed by a Synchronous Motor :

The expression for power developed by the synchronous motor in terms of α, θ, V, E_b, and Z_s are as follows :

Let

V = Supply voltage

E_b = Back emf / phase

α = Load angle

θ = Internal or Impedance angle = Tan^{-1} (X_r / Z_s)

I_a = Armature current / phase = E_r / Z_s

$Z_s = R_a + J X_s$ = Synchronous impedance

Mechanical power developed / phase,

$$P_m = \frac{E_b V}{Z_s}\cos(\theta - \alpha) - \frac{E_b^2}{Z_s}\cos\theta$$

The armature resistance is neglected
If R_a is neglected, then $Z_s \approx X_s$ and $\theta = 90°$. substituting these values in the above equation.

$$P_m = \frac{E_b V}{X_s}\cos(90 - \alpha) - \frac{E_b^2}{X_s}\cos 90^0$$

$$P_m = \frac{E_b V}{X_s}\sin\alpha$$

Synchronous Motor:Synchronous Motor with Different Excitations

Synchronous Motor with Different Excitations

A synchronous motor is said to have normal excitation when its Eb = V . If field excitation is such that Eb < V , the motor is said to be under-excited. In both these conditions, it has a lagging power factor as shown in Fig. 38.12.

On the other hand, if d.c. field excitation is such that Eb > V , then motor is said to be over-excited and draws a leading current, as shown in Fig. 38.13 (a). There will be some value of excitation for which armature current will be in phase with V , so that power factor will become unity, as shown in Fig. 38.13 (b).

The value of a and back e.m.f. Eb can be found with the help of vector diagrams for various power factors, shown in Fig. 38.14.

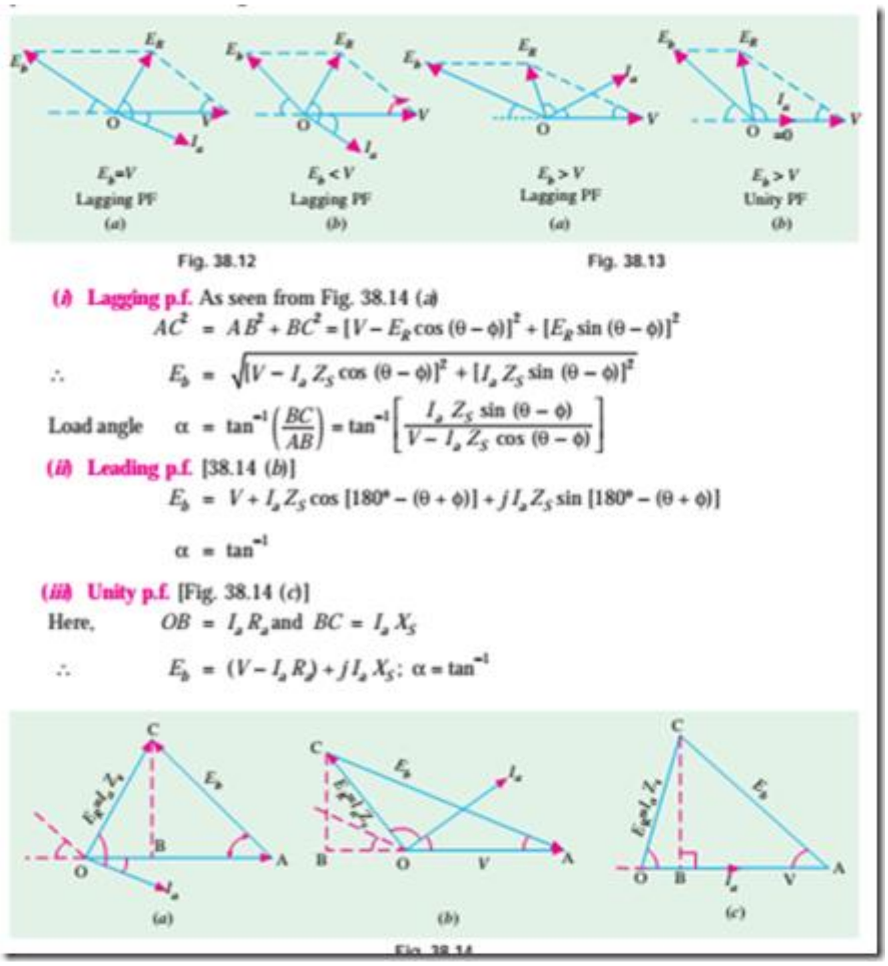


Fig. 38.12

Fig. 38.13

(i) Lagging p.f. As seen from Fig. 38.14 (a)

$$AC^2 = AB^2 + BC^2 = [V - E_R \cos(\theta - \phi)]^2 + [E_R \sin(\theta - \phi)]^2$$

$$\therefore \quad E_b = \sqrt{[V - I_a Z_S \cos(\theta - \phi)]^2 + [I_a Z_S \sin(\theta - \phi)]^2}$$

$$\text{Load angle} \quad \alpha = \tan^{-1}\left(\frac{BC}{AB}\right) = \tan^{-1}\left[\frac{I_a Z_S \sin(\theta - \phi)}{V - I_a Z_S \cos(\theta - \phi)}\right]$$

(ii) Leading p.f. [38.14 (b)]

$$E_b = V + I_a Z_S \cos[180° - (\theta + \phi)] + j I_a Z_S \sin[180° - (\theta + \phi)]$$

$$\alpha = \tan^{-1}$$

(iii) Unity p.f. [Fig. 38.14 (c)]

$$\text{Here,} \quad OB = I_a R_a \text{ and } BC = I_a X_S$$

$$\therefore \quad E_b = (V - I_a R_a) + j I_a X_S ; \ \alpha = \tan^{-1}$$

Fig. 38.14

Effect of Increased Load with Constant Excitation

We will study the effect of increased load on a synchronous motor under conditions of normal, under and over-excitation (ignoring the effects of armature reaction). With normal excitation, Eb = V , with under excitation, Eb < V and with over-excitation, Eb > V . Whatever the value of excitation, it would be kept constant during our discussion. It would also be assumed that Ra is negligible as compared to X S so that phase angle between ER and Ia i.e., q = 90º.

(i) Normal Excitation.

Fig. 38.15. (a) shows the condition when motor is running with light load so that (i) torque angle.

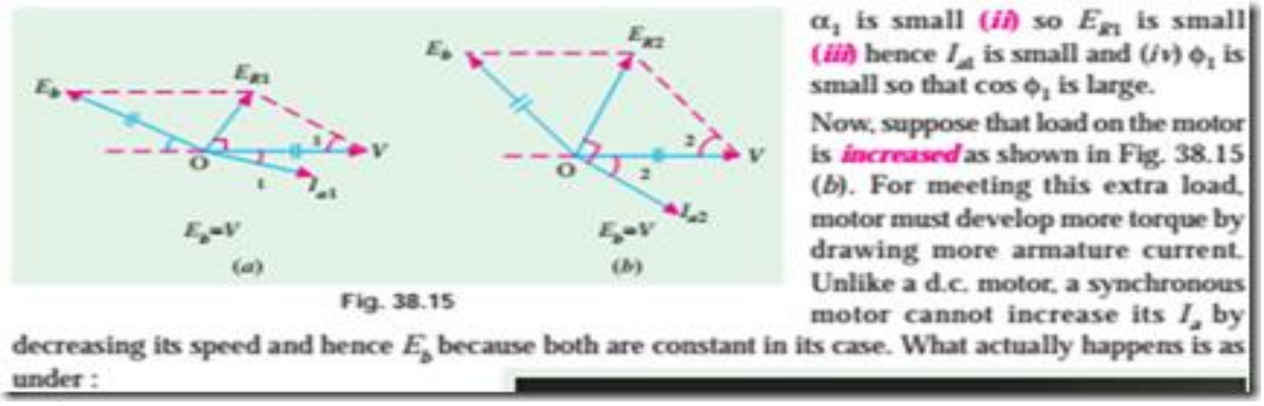
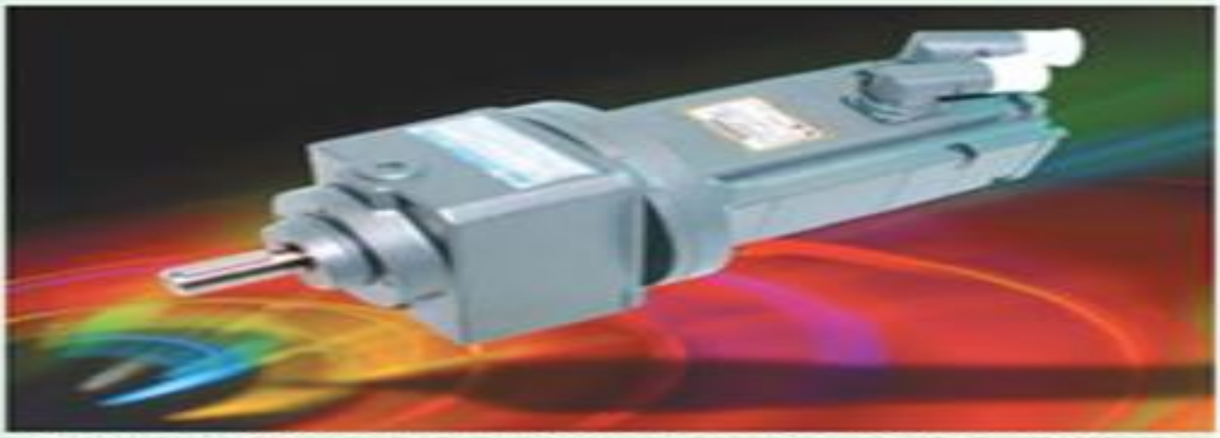


Fig. 38.15

α_1 is small *(ii)* so E_{R1} is small *(iii)* hence I_{a1} is small and *(iv)* ϕ_1 is small so that cos ϕ_1 is large.

Now, suppose that load on the motor is ***increased*** as shown in Fig. 38.15 (*b*). For meeting this extra load, motor must develop more torque by drawing more armature current. Unlike a d.c. motor, a synchronous motor cannot increase its I_a by decreasing its speed and hence E_b because both are constant in its case. What actually happens is as under :

1. rotor falls back in phase i.e., load angle increases to a2 as shown in Fig. 38.15 (b),
2. the resultant voltage in armature is increased considerably to new value ER2,
3. as a result, Ia1 increases to Ia2, thereby increasing the torque developed by the motor,
4. f1 increases to f2, so that power factor decreases from cos f1 to the new value cos f2.



Geared motor added to synchronous servo motor line offers a wide range of transmission ratios, and drive torques.

Since increase in Ia is much greater than the slight decrease in power factor, the torque developed by the motor is increased (on the whole) to a new value sufficient to meet the extra load put on the motor. It will be seen that essentially it is by increasing its Ia that the motor is able to carry the extra load put on it.

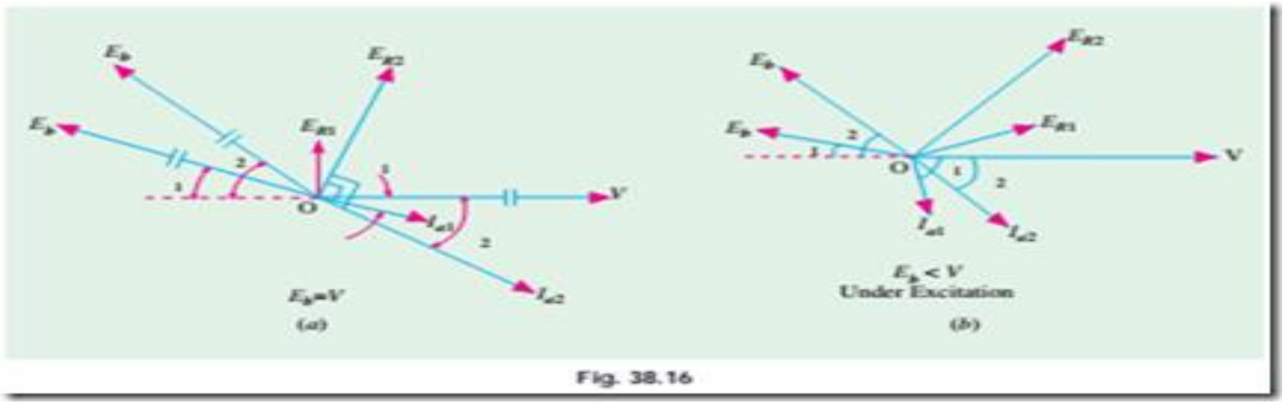


Fig. 38.16

A phase summary of the effect of increased load on a synchronous motor at normal excitation is shown in Fig. 38.16 (a) It is seen that there is a comparatively much greater increase in Ia than in f.

(ii) Under-excitation

As shown in Fig. 38.16 (b), with a small load and hence, small torque angle a1, Ia1 lags behind V by a large phase angle f1 which means poor power factor. Unlike normal excitation, a much larger armature current must flow for developing the same power because of poor power factor. That is why Ia1 of Fig. 38.16 (b) is larger than Ia1 of Fig. 38.15 (a).

As load increases, ER1 increases to ER2, consequently Ia1 increases to Ia2 and p.f. angle decreases from f1 to f2 or p.f. increases from cos f1 to cos f2. Due to increase both in Ia and p.f., power generated by the armature increases to meet the increased load. As seen, in this case, change in power factor is more than the change in Ia.

(iii) Over-excitation

When running on light load, a1 is small but Ia1 is comparatively larger and leads V by a larger angle f1. Like the under-excited motor, as more load is applied, the power factor improves and approaches unity. The armature current also increases thereby producing the necessary increased armature power to meet the increased applied load (Fig. 38.17). However, it should be noted that in this case, power factor angle f decreases (or p.f. increases) at a faster rate than the armature current thereby producing the necessary increased power to meet the increased load applied to the motor.

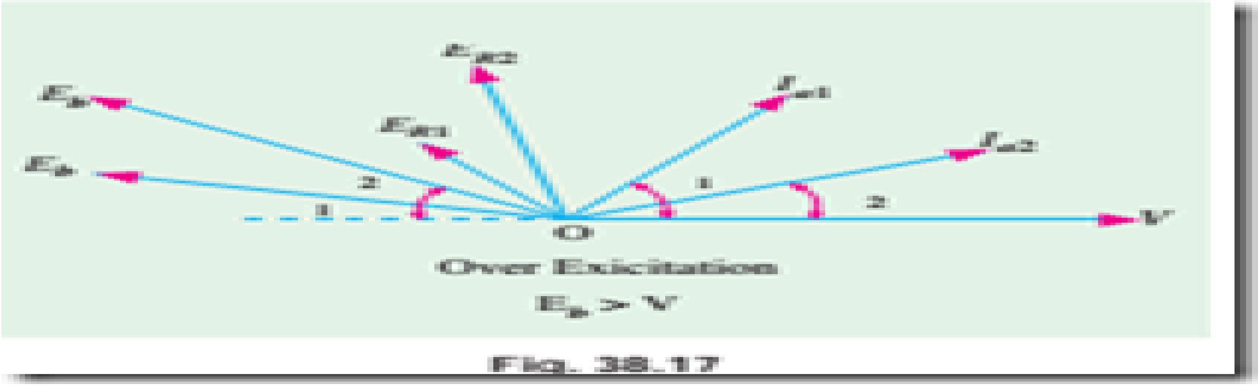


Fig. 38.17

Summary

The main points regarding the above three cases can be summarized as under :

1. As load on the motor increases, Ia increases regardless of excitation.
2. For under-and over-excited motors, p.f. tends to approach unity with increase in load.
3. Both with under-and over-excitation, change in p.f. is greater than in Ia with increase in load.
4. With normal excitation, when load is increased change in Ia is greater than in p.f. which tends to become increasingly lagging.

Example 38.2. A 20-pole, 693-V, 50-Hz, 3-f, D-connected synchronous motor is operating at no-load with normal excitation. It has armature ressistance per phase of zero and synchronous reactance of 10 W . If rotor is retarded by 0.5º (mechanical) from its synchronous position, compute.

(i) rotor displacement in electrical degrees

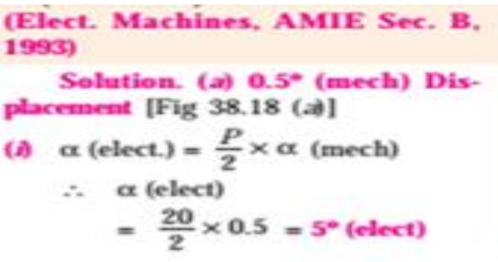
(ii) armature emf / phase

(iii) armature current / phase

(iv) power drawn by the motor

(v) power developed by armature

How will these quantities change when motor is loaded and the rotor displacement increases to 5º (mechanical) ?



(Elect. Machines, AMIE Sec. B, 1993)

Solution. (*a*) 0.5° (mech) Displacement [Fig 38.18 (*a*)]

(*i*) $\alpha \text{ (elect.)} = \frac{P}{2} \times \alpha \text{ (mech)}$

$\therefore \quad \alpha \text{ (elect)} = \frac{20}{2} \times 0.5 = 5° \text{ (elect)}$

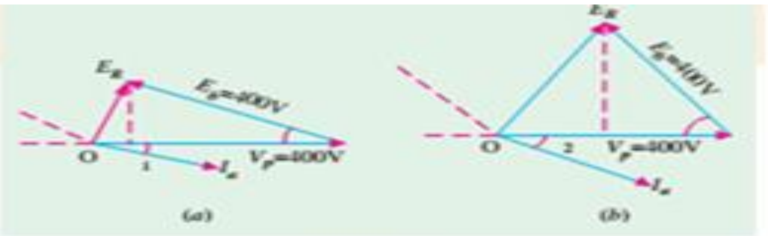
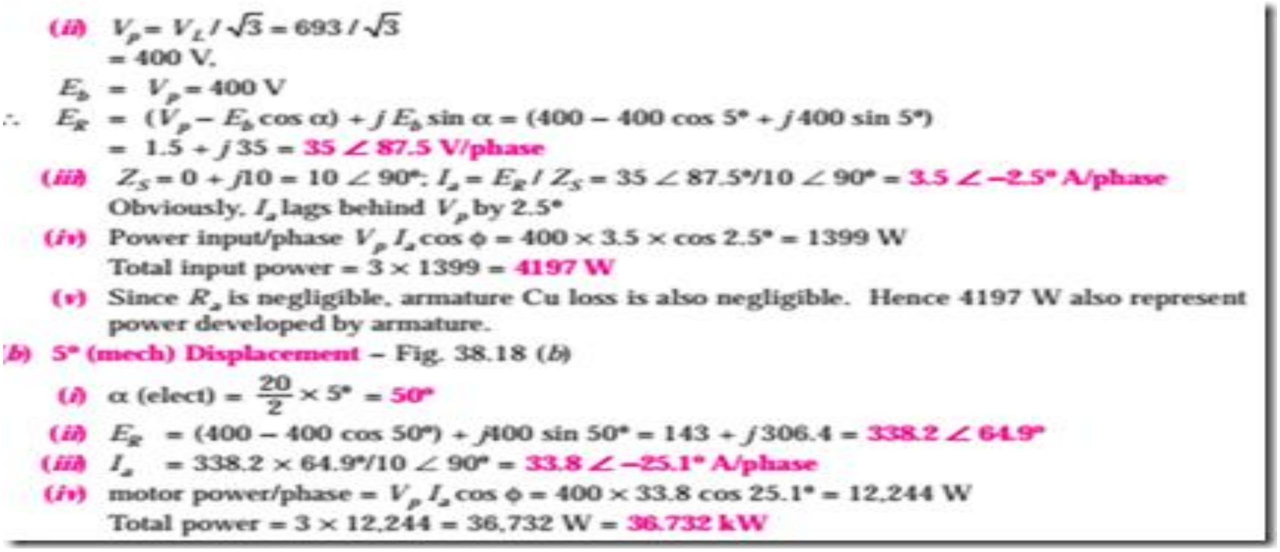


Fig. 38.18



(*ii*) $V_p = V_L / \sqrt{3} = 693 / \sqrt{3}$
$= 400$ V.
$E_b = V_p = 400$ V
$\therefore \quad E_R = (V_p - E_b \cos \alpha) + j E_b \sin \alpha = (400 - 400 \cos 5° + j 400 \sin 5°)$
$= 1.5 + j35 = 35 \angle 87.5$ V/phase

(*iii*) $Z_S = 0 + j10 = 10 \angle 90°$; $I_a = E_R / Z_S = 35 \angle 87.5° / 10 \angle 90° = 3.5 \angle -2.5°$ A/phase
Obviously, I_a lags behind V_p by 2.5°

(*iv*) Power input/phase $V_p I_a \cos \phi = 400 \times 3.5 \times \cos 2.5° = 1399$ W
Total input power $= 3 \times 1399 = 4197$ W

(*v*) Since R_a is negligible, armature Cu loss is also negligible. Hence 4197 W also represent power developed by armature.

(*b*) 5° (mech) Displacement – Fig. 38.18 (*b*)

(*i*) $\alpha \text{ (elect)} = \frac{20}{2} \times 5° = 50°$

(*ii*) $E_R = (400 - 400 \cos 50°) + j400 \sin 50° = 143 + j306.4 = 338.2 \angle 64.9°$

(*iii*) $I_a = 338.2 \times 64.9° / 10 \angle 90° = 33.8 \angle -25.1°$ A/phase

(*iv*) motor power/phase $= V_p I_a \cos \phi = 400 \times 33.8 \cos 25.1° = 12{,}244$ W
Total power $= 3 \times 12{,}244 = 36{,}732$ W $= 36.732$ kW

1. rotor displacement increases from 5º (elect) to 50º (elect) i.e. Eb falls back in phase considerably.
2. ER increases from 35 V to 338 V/phase

3. Ia increases from 3.5 A to 33.8 A

4. angle f increases from 2.5º to 25.1º so that p.f. decreases from 0.999 (lag) to 0.906 (lag)

5. increase in power is almost directly proportional to increase in load angle. Obviously, increase in Ia is much more than decrease in power factor.

It is interesting to note that not only power but even Ia, ER and f also increase almost as many times as a.Special Illustrative Example 38.3 Case of Cylindrical Rotor Machine :

A 3-Phase synchronous machine is worked as follows: Generator – mode : 400 V/Ph, 32 A/Ph, Unity p.f. XS = 10 ohms. Motoring – mode : 400 V/Ph, 32 A/Ph, Unity p.f. , XS = 10 ohms. Calculate E and d in both the cases and comment.

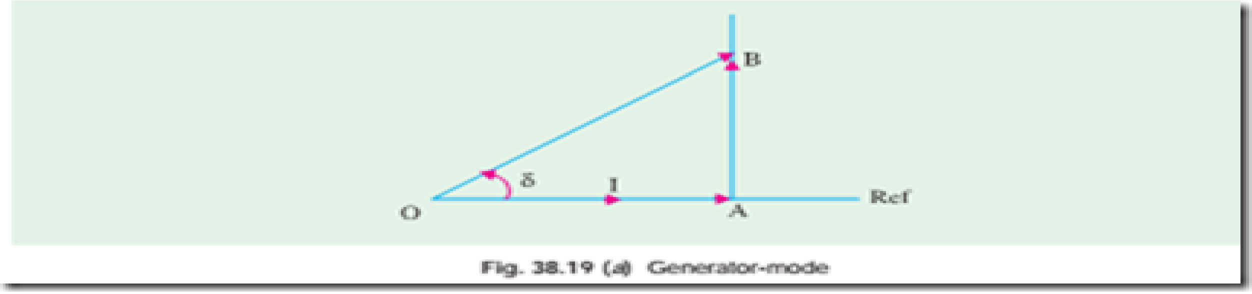
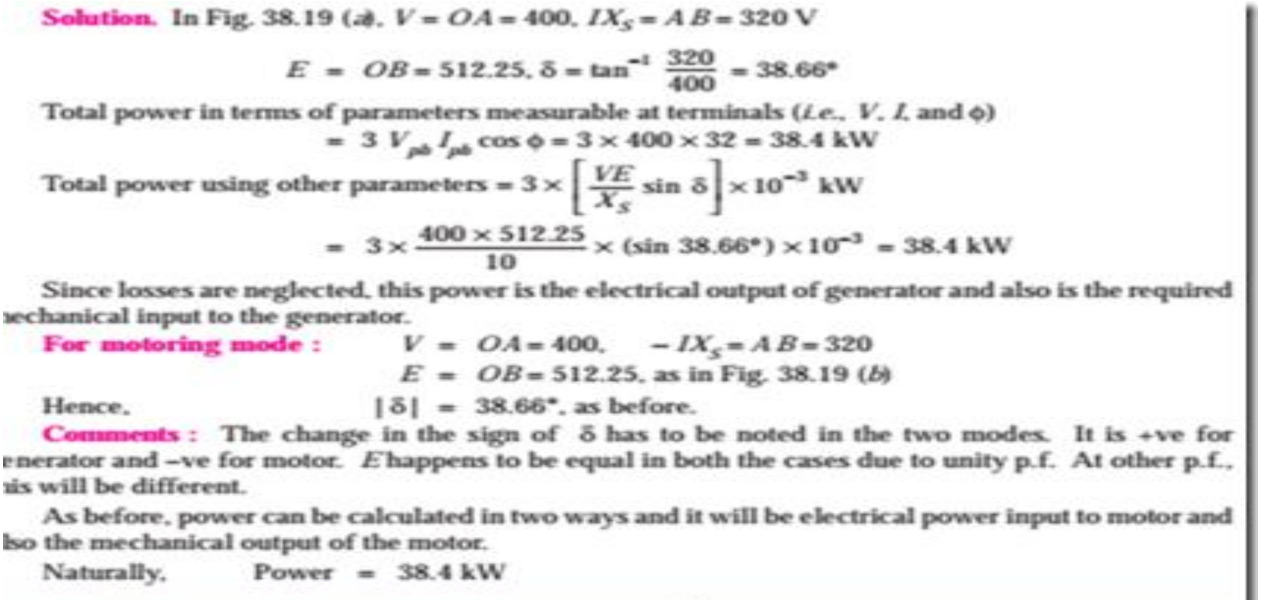


Fig. 38.19 (*a*) Generator-mode



Solution. In Fig. 38.19 (*a*), $V = OA = 400$, $IX_S = AB = 320$ V

$$E = OB = 512.25,\ \delta = \tan^{-1}\frac{320}{400} = 38.66°$$

Total power in terms of parameters measurable at terminals (*i.e.*, *V*, *I*, and ϕ)

$$= 3\ V_{ph}\ I_{ph} \cos\phi = 3 \times 400 \times 32 = 38.4 \text{ kW}$$

$$\text{Total power using other parameters} = 3 \times \left[\frac{VE}{X_S}\sin\delta\right] \times 10^{-3} \text{ kW}$$

$$= 3 \times \frac{400 \times 512.25}{10} \times (\sin 38.66°) \times 10^{-3} = 38.4 \text{ kW}$$

Since losses are neglected, this power is the electrical output of generator and also is the required echanical input to the generator.

For motoring mode : $V = OA = 400$, $-IX_S = AB = 320$

$E = OB = 512.25$, as in Fig. 38.19 (*b*)

Hence, $|\delta| = 38.66°$, as before.

Comments : The change in the sign of δ has to be noted in the two modes. It is +ve for enerator and –ve for motor. *E* happens to be equal in both the cases due to unity p.f. At other p.f., is will be different.

As before, power can be calculated in two ways and it will be electrical power input to motor and lso the mechanical output of the motor.

Naturally, Power = 38.4 kW

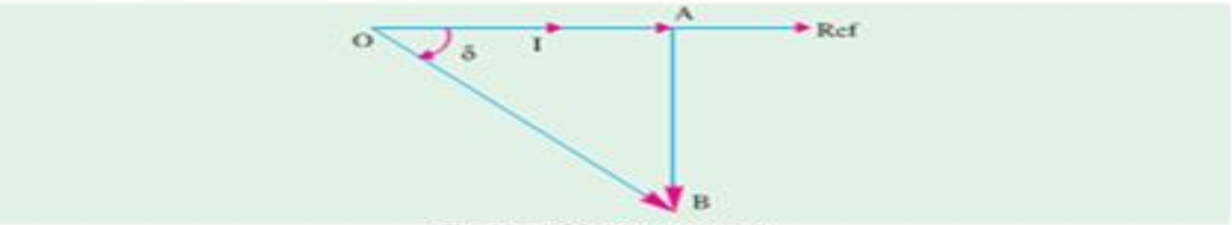


Fig. 38.19 (*b*) Motoring mode

Effect of Changing Excitation on Constant Load

As shown in Fig. 38.20 (a), suppose a synchronous motor is operating with normal excitation (Eb = V) at unity p.f. with a given load. If Ra is negligible as compared to X S, then Ia lags ER by 90º and is in phase with V because p.f. is unity. The armature is drawing a power of V .Ia per phase which is enough to meet the mechanical load on the motor. Now, let us discuss the effect of decreasing or increasing the field excitation when the load applied to the motor remains constant.

(a) Excitation Decreased

As shown in Fig. 38.20 (b), suppose due to decrease in excitation, back e.m.f. is reduced to Eb1 at the same load angle a1. The resultant voltage ER1 causes a lagging armature current Ia1 to flow. Even though Ia1 is larger than Ia in magnitude it is incapable of producing necessary power V Ia for carrying the constant load because Ia1 cos f1 component is less than Ia so that V Ia1 cos f1 < V Ia.

Hence, it becomes necessary for load angle to increase from a1 to a2. It increases back e.m.f. from Eb1 to Eb2 which, in turn, increases resultant voltage from ER1 to ER2. Consequently, armature current increases to Ia2 whose in-phase component produces enough power (V Ia2 cos f2) to meet the constant load on the motor.

(b) Excitation Increased

The effect of increasing field excitation is shown in Fig. 38.20 (c) where increased Eb1 is shown at the original load angle a1. The resultant voltage ER1 causes a leading current Ia1 whose in-phase component is larger than Ia. Hence, armature develops more power than the load on the motor. Accordingly, load angle decreases from a1 to a2 which decreases resultant voltage from ER1 to ER2. Consequently, armature current decreases from Ia1 to Ia2 whose in-phase component Ia2 cos f2 = Ia. In that case, armature develops power sufficient to carry the constant load on the motor.

Hence, we find that variations in the excitation of a synchronous motor running with a given load produce variations in its load angle only.

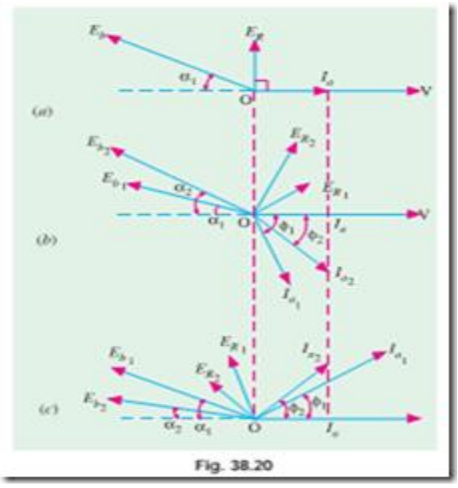


Fig. 38.20

Different Torques of a Synchronous Motor

Various torques associated with a synchronous motor are as follows:

1. starting torque
2. running torque
3. pull-in torque and
4. pull-out torque

(a) Starting Torque

It is the torque (or turning effort) developed by the motor when full voltage is applied to its stator (armature) winding. It is also sometimes called breakaway torque. Its value may be as low as 10% as in the case of centrifugal pumps and as high as 200 to 250% of full-load torque as in the case of loaded reciprocating two-cylinder compressors.

(b) Running Torque

As its name indicates, it is the torque developed by the motor under running conditions. It is determined by the horse-power and speed of the driven machine. The peak horsepower determines the maximum torque that would be required by the driven machine. The motor must have a break- down or a maximum running torque greater than this value in order to avoid stalling.

Torque motors are designed to privide maximum torque at locked rotor or near stalled conditions

(c) Pull-in Torque

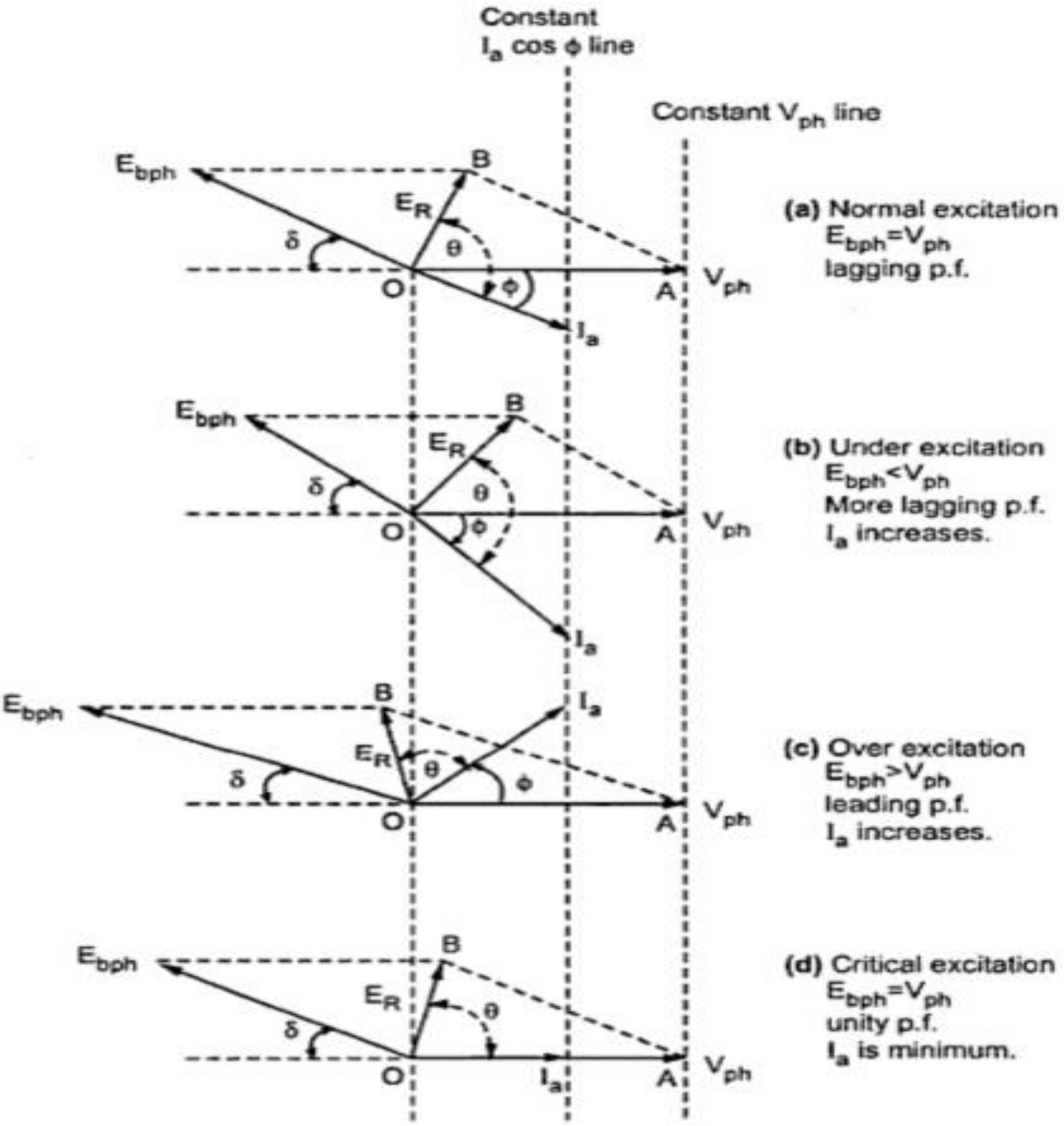
A synchronous motor is started as induction motor till it runs 2 to 5% below the synchronous speed. Afterwards, excitation is switched on and the rotor pulls into step with the synchronously- rotating stator field. The amount of torque at which the motor will pull into step is called the pull-in torque.

(d) Pull-out Torque

The maximum torque which the motor can develop without pulling out of step or synchronism is called the pull-out torque.

Normally, when load on the motor is increased, its rotor progressively tends to fall back in phase by some angle (called load angle) behind the synchronously-revolving stator magnetic field though it keeps running synchronously. Motor develops maximum torque when its rotor is retarded by an angle of 90^o (or in other words, it has shifted backward by a distance equal to half the distance between adjacent poles). Any further increase in load will cause the motor to pull out of step (or synchronism) and stop.

Operation Of Synchronous Motor At Constant Load Variable Excitation



We have seen previously that when load changes, for constant excitation, current drawn by the motor increases. But if excitation i.e. field current is changed keeping load constant, the synchronous motor reacts by by changing its power factor of operation. This is most interesting feature of synchronous motor. Let us see the details of such operation.

Consider a synchronous motor operating at a certain load. The corresponding load angle is ?.
At start, consider normal behavior of the synchronous motor, where excitation is adjusted to get $E_b = V$ i.e. induced e.m.f. is equal to applied voltage. Such an excitation is called Normal Excitation of the motor. Motor is drawing certain current from the supply and power input to the motor is say P_{in}. The power factor of the motor is lagging in nature as shown in the Fig. 1(a).

Now when excitation is changed, changes but there is hardly any change in the losses of the motor. So the power input also remains same for constant load demanding same power output.
Now $P_{in} = ?3\ V_L I_L \cos ? = 3 (V_{ph} I_{ph} \cos ?)$

Most of the times, the voltage applied to the motor is constant. Hence for constant power input as V_{ph} is constant, '$I_{ph} \cos ?$' remains constant.

Note : So far this entire operation of variable excitation it is necessary to remember that the cosine component of armature current, $I_a \cos ?$ remains constant.
So motor adjusts its cos ? i.e. p.f. nature and value so that $I_a \cos ?$ remains constant when excitation of the motor is changed keeping load constant. This is the reason why synchronous motor reacts by changing its power factor to variable excitation conditions.

1.1 Under Excitation

When the excitation is adjusted in such a way that the magnitude of induced e.m.f. is less than the applied voltage ($E_b < V$) the excitation is called Under Excitation. Due to this, E_R increases in magnitude. This means for constant Z_s, current drawn by the motor increases. But E_R phase shifts in such a way that, phasor I_a also shifts (as $E_R \wedge I_a = ?$) to keep $I_a \cos ?$ component constant. This is shown in the Fig. 1(b). So in under excited condition, current drawn by the motor increases. The p.f. cos ? decreases and becomes more and more lagging in nature.

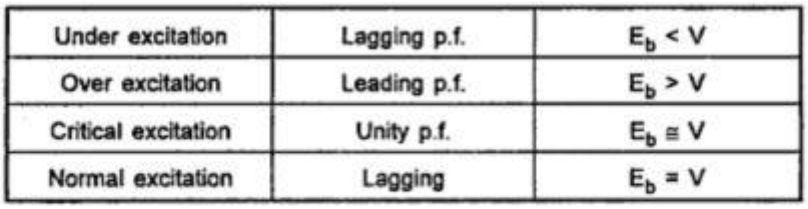
1.2 Over Excitation

The excitation to the field winding for which the induced e.m.f. becomes greater than applied voltage ($E_b < V$), is called over excitation. Due to increased magnitude of E_b, E_R also increases in magnitude. But the phase of E_R also changes. Now = $E_R \wedge I_a = ?$is constant, hence I_a also changes its phase. So ? changes. The I_a increases to keep $I_a \cos ?$ constant as shown in Fig.1(c). The phase of E_R changes so that I_a becomes leading with respect to V_{ph} in over excited condition. So power factor of the motor becomes leading in nature. So overexcited synchronous motor works on leading power factor. So power factor decreases as over excitation increases but it becomes more and more leading in nature.

1.3 Critical Excitation

When the excitation is changed, the power factor changes. The excitation for which the power factor of the motor is unity (cos ? = 1) is called critical excitation. Then I_{aph} is in phase with V_{ph}. Now I_a cos ? must be constant, cos ? = 1 is at its maximum hence motor has to draw minimum current from supply for unity power factor condition.

So for critical excitation, cos ? = 1 and current drawn by the motor is minimum compared to current drawn by the motor for various excitation conditions. This is shown in the Fig. 1(d).



Under excitation	Lagging p.f.	$E_b < V$
Over excitation	Leading p.f.	$E_b > V$
Critical excitation	Unity p.f.	$E_b \cong V$
Normal excitation	Lagging	$E_b = V$

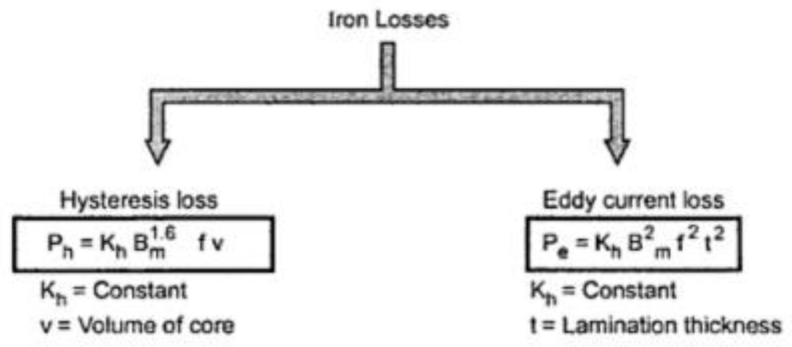


Fig. 1 Constant load variable excitation operation

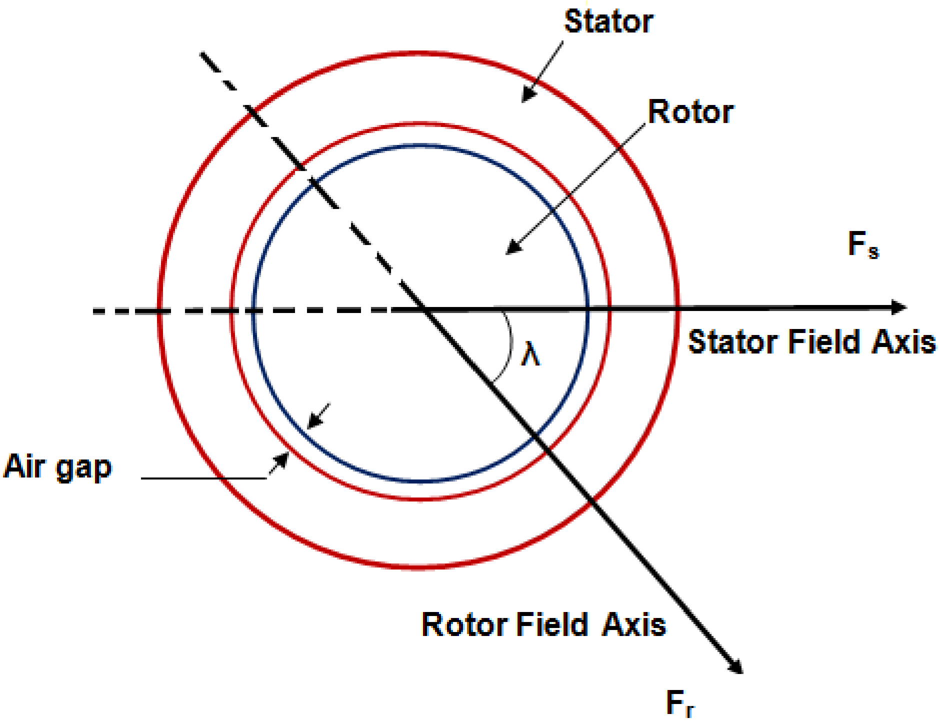
Torque Equation for Synchronous Machine

We know that torque equation in synchronous motor or generator is directly proportional to the stator filed strength, rotor field strength and the sine of angle between them. This is true for all rotating electrical machine.

If F_s, F_r and λ be the stator field strength, rotor field strength and angle between F_s & F_r, then the torque is given as

$T_e = F_s F_r \mathrm{Sin}\lambda$

The above torque equation is a general equation applicable for all rotating electrical machine. In this post we will derive a general torque equation for synchronous machine. For this purpose, let us consider a uniform air gap two pole machine as shown below.



Current in the stator winding produces stator mmf which is assumed to be sinusiodally distributed in the air gap periphery. The peak value of this stator mmf Fs is directed along the stator winding axis as shown in figure. In the above figure, Fs is taken horizontal with Fs directed from left to right. Similarly, rotor current produces rotor mmf which is also assumed sinusiodally distributed in the air gap. The peak value of rotor mmf Fr is along the rotor winding axis as shown in figure. It should be noted that Fs and Fr is the peak value of resultant mmf due to all stator and rotor winding.

These stator and rotor mmf in turn causes appearance of stator and rotor poles. Stator mmf Fs causes appearance of North pole in the left side whereas South pole at the right side of stator. Similarly, North and South pole are produced due to rotor mmf as shown in figure. These stator and rotor magnetic poles interact with each other and tend to align their magnetic axis. This results in development of electromagnetic torque.

In the above figure, the length of air gap is ‘g’ and average radius i.e. average of stator and rotor radii is ‘r’. The effective axial length of synchronous machine is ‘l’.

For deriving general torque equation for synchronous motor / generator, following assumptions are made:
The stator and rotor iron have infinite permeability. This effectively means that saturation is neglected.
All the magnetic flux crosses the air gap perpendicularly. This means that flux leakage is assume to be absent.

The air gap length is very small when compared to the axial length of synchronous machine. This means that the value of flux density at stator surface, rotor surface and at any point in the air gap is same.

Only fundamental sine component of stator and rotor mmf wave is considered.

Based on the above assumptions, the torque equation for any rotating electrical machine is given as

$$\mathbf{T_e = -(\pi/8)P^2 \varnothing F_s \sin\delta_s \ Nm}$$

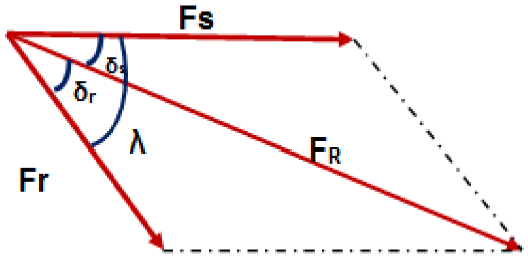
$$\mathbf{= -(\pi/8)P^2 \varnothing F_r \sin\delta_r \ Nm}$$

P = Number of poles

Ø = Resultant air gap flux per pole

F_r = Rotor mmf

F_s = Stator mmf



In the above phasor, FR is the resultant of stator mmf F_s and rotor mmf F_r. The angle between F_r & F_R i.e. δ_r is called the **load angle**. Similarly, the angle between the resultant air gap flux F_R and Stator mmf F_s i.e. δ_s is called load angle. The angle λ between the stator and rotor mmf is called the torque angle.

The negative sign in the torque equation of synchronous machine implies that electromagnetic torque acts in such a direction to minimize the torque angle λ. It must be noted here that, the above torque equation is valid not only for synchronous motor or generator rather it is valid for all rotating electrical machine.

Torque and Power Relations

Motor Torque

Gross torque, T =9.55 Pm/Ns N-M where Pm = Gross motor output in watts = Eb Ia cos(d - ϕ)

Ns = Synchronous speed in r.p.m.

Shaft torque, Tsh = 9.55 Psh_{out}/Ns N-M

It may be seen that torque is directly proportional to the mechanical power because rotor speed (i.e., Ns) is fixed.

Mechanical Power Developed

Neglecting the armature resistance Fig: 2.25 shows the phasor diagram of an under-excited synchronous motor driving a mechanical load. Since armature resistance Ra is assumed zero. tanq= Xs/Ra = ¥ and hence q =90°.

Input power/phase = V Ia cos ϕ

Since Ra is assumed zero, stator Cu loss $(IRa)^2$ will be zero. Hence input power is equal to the mechanical power Pm developed by the motor.

Mechanical power developed/ phase, Pm = V Ia cos ϕ, referring to the phasor diagram in Fig: .

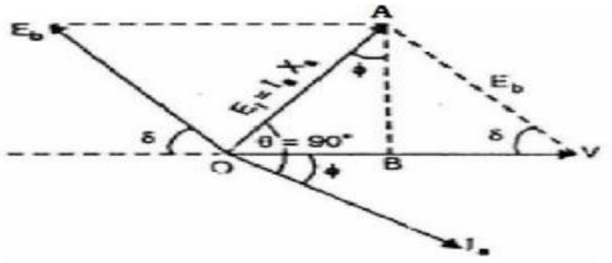
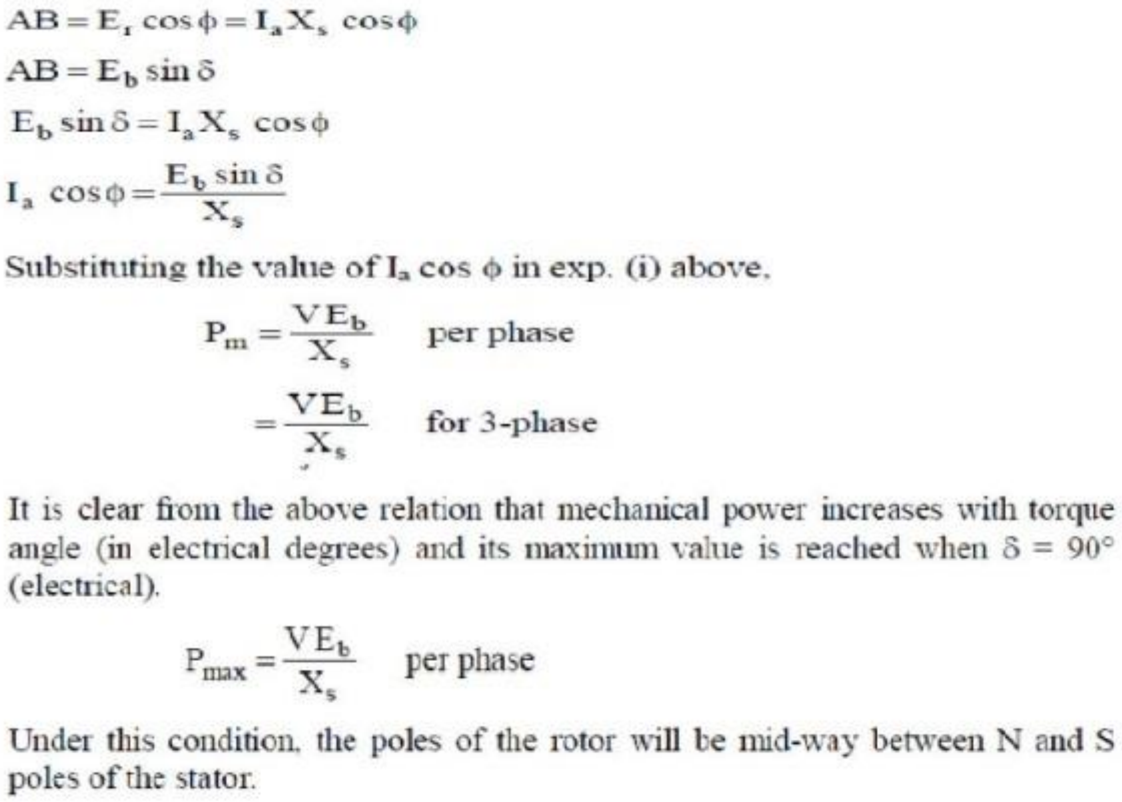


Fig:



$$AB = E_r \cos\phi = I_a X_s \cos\phi$$

$$AB = E_b \sin\delta$$

$$E_b \sin\delta = I_a X_s \cos\phi$$

$$I_a \cos\phi = \frac{E_b \sin\delta}{X_s}$$

Substituting the value of $I_a \cos\phi$ in exp. (i) above.

$$P_m = \frac{VE_b}{X_s} \quad \text{per phase}$$

$$= \frac{VE_b}{X_s} \quad \text{for 3-phase}$$

It is clear from the above relation that mechanical power increases with torque angle (in electrical degrees) and its maximum value is reached when δ = 90° (electrical).

$$P_{max} = \frac{VE_b}{X_s} \quad \text{per phase}$$

Under this condition, the poles of the rotor will be mid-way between N and S poles of the stator.

V-Curves and Inverted V-Curves:

It is clear from above discussion that if excitation is varied from very low (under excitation) to very high (over excitation) value, then current Ia decreases, becomes minimum at unity p.f. and then again increases.

V-Curves and Inverted V-Curves:

It is clear from above discussion that if excitation is varied from very low (under excitation) to very high (over excitation) value, then current Ia decreases, becomes minimum at unity p.f. and then again increases. But initial lagging current becomes unity and then becomes leading in nature. This can be shown as in the Fig: 2.26.

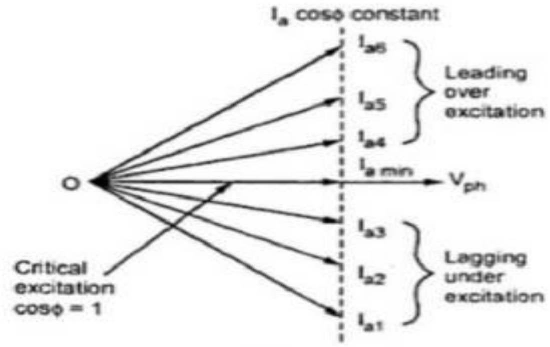


Fig: 2.26

Excitation can be increased by increasing the field current passing through the field winding of synchronous motor. If graph of armature current drawn by the motor (Ia) against field current (I_f) is plotted, then its shape looks like an English alphabet V. If such graphs are obtained at various load conditions we get family of curves, all looking like V. Such curves are called V-curves of synchronous motor. These are shown in the Fig: 2.27 (a).

As against this, if the power factor (cos ϕ) is plotted against field current (If), then the shape of the graph looks like an inverted V. Such curves obtained by plotting p.f. against If, at various load conditions are called Inverted V-curves of synchronous motor. These curves are shown in the Fig: 2.27 (b).

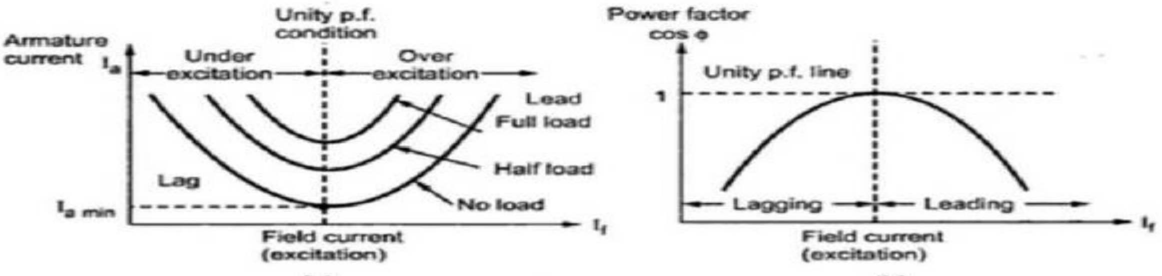


Fig:

Typically, the synchronous machine V-curves are provided by the manufacturer so that the user can determine the resulting operation under a given set of conditions.

Hunting and Damper Winding:

Hunting:

Sudden changes of load on synchronous motors may sometimes set up oscillations that are superimposed upon the normal rotation, resulting in periodic variations of a very low frequency in speed. This effect is known as hunting or phase-swinging. Occasionally, the trouble is aggravated by the motor having a natural period of oscillation approximately equal to the hunting period. When the synchronous motor phase-swings into the unstable region, the motor may fall out of synchronism.

Damper winding:

The tendency of hunting can be minimized by the use of a damper winding. Damper windings are placed in the pole faces. No emfs are induced in the damper bars and no current flows in the damper winding, which is not operative. Whenever any irregularity takes place in the speed of rotation, however, the polar flux moves from side to side of the pole, this movement causing the flux to move backwards and forwards across the damper bars. Emfs are induced in the damper bars forwards across the damper winding. These tend to damp out the superimposed oscillatory motion by absorbing its energy. The damper winding, thus, has no effect upon the normal average speed, it merely tends to damp out the oscillations in the speed, acting as a kind of electrical flywheel. In the case of a three-phase synchronous motor the stator currents set up a rotating mmf rotating at uniform speed and if the rotor is rotating at uniform speed, no emfs are induced in the damper bars. Fig: shows a salient pole synchronous motor with damper winding.

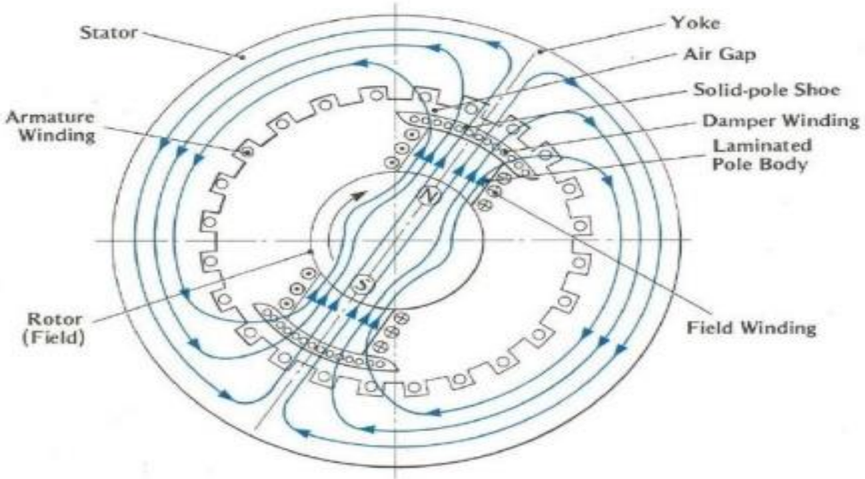


Fig: