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

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

COURSE MATERIAL

EE 402 SPECIAL ELECTRICAL MACHINES

VISION OF THE INSTITUTION
To mould true citizens who are millennium leaders and catalysts of change through excellence in education.
MISSION OF THE INSTITUTION

NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values.

We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2002
- Course offered: B.Tech Electrical and Electronics Engineering
- M.Tech (Energy Systems)
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

To excel in technical education and research in the field of Electrical & Electronics Engineering by imparting innovative engineering theories, concepts and practices to improve the production and utilization of power and energy for the betterment of the Nation

DEPARTMENT MISSION

1) To offer quality education in Electrical and Electronics Engineering and prepare the students for professional career and higher studies.

2) To create research collaboration with industries for gaining knowledge about real-time problems.

3) To prepare students with sound technical knowledge

4) To make students socially responsible

PROGRAMME EDUCATIONAL OBJECTIVES

1. Graduates shall have a good foundation in the fundamental and practical aspects of Mathematics and Engineering Sciences so as to build successful and enriching careers in the field of Electrical Engineering and allied areas

2. Graduates shall learn and adapt themselves to the latest technological developments in the field of Electrical & Electronics Engineering which will in turn motivate them to excel in their domains and shall pursue higher education and research

3. Graduates shall have professional ethics and good communication ability along with entrepreneurial skills and leadership skills, so that they can succeed in multidisciplinary and diverse fields.

PROGRAM OUTCOME (PO'S)

Engineering Graduates will be able to:

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

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

PO 3. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO 4. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO 5. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO 6. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO 7. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

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

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

PO 10. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO 11. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO 12. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOME(PSO'S)

PSO 1: Apply Science, Engineering, Mathematics through differential and Integral Calculus, Complex Variables to solve Electrical Engineering Problems

PSO 2: Demonstrate proficiency in the use of software and hardware to be required to practice electrical engineering profession.

PSO 3. Apply the knowledge of Ethical and Management principles required to work in a team as well as to lead a team.

Course code	Course Name	L-T-P - Credits	Year of Introduction
EE402	Special Electrical Machines	3-0-0-3	2016

Prerequisite: Nil

Course Objectives

- To get an overview of some of the special machines for control and industrial applications

Syllabus

AC Servomotors – construction – operation - DC servomotors – Stepper motor – operation – types-modes of excitation – AC series motor – Universal motor – Hysteresis motor – Reluctance motor – Switched reluctance motor – Permanent magnet DC motor – Brushless DC motor – Linear motors – Linear induction motors.

Expected outcome.

- The students will gain knowledge in the construction and principle of operation of certain special electrical machines having various applications.

Text Book:

E. G. Janardhanan, '*Special Electrical Machines*' PHI Learning Private Limited.

References:

1. Irving L. Kosow.'*Electrical Machinery and Transformers*', Oxford Science Publications.
2. T. J. E. Miller, '*Brushless PM and Reluctance Motor Drives*'.C.Larendon Press, Oxford.
3. Theodore Wildi, '*Electric Machines, Drives and Power Systems*', Prentice Hall India Ltd.
4. Veinott & Martin,'*Fractional & Subfractional hp Electric Motors*'.McGraw Hill International Edn.

Course Plan

Module	Contents	Hours	Sem. Exam Marks
I	AC Servomotors- Construction-principle of operation – performance characteristics – damped AC servomotors – Drag cup servomotor – applications. DC servomotors – field and armature controlled DC servomotors – permanent magnet armature controlled – series split field DC servomotor.	7	15%
II	Stepper motors – Basic principle – different types – variable reluctance- permanent magnet – hybrid type – comparison – theory of operation – monofilar and bifilar windings – modes of excitation – drive circuits – static and dynamic characteristics – applications	7	15%
FIRST INTERNAL EXAMINATION			
III	Single phase special electrical machines – AC series motor-construction – principle of working – phasor diagram – universal motor Hysteresis motor- constructional details- principle of operation – torque-slip characteristics – applications.	7	15%
IV	Reluctance motors – principle of operation – torque equation – torque slip characteristics-applications. Switched reluctance motors – principle of operation – power converter circuits – torque equation – different types – comparison – applications.	7	15%

SECOND INTERNAL EXAMINATION			
V	Permanent Magnet DC Motors – construction – principle of working. Brushless dc motor – construction – trapezoidal type-sinusoidal type – comparison – applications.	7	20%
VI	Linear motors – different types – linear reluctance motor – linear synchronous motors – construction – comparison. Linear induction motors – Expression for linear force – equivalent circuit – applications.	7	20%
END SEMESTER EXAM			

QUESTION PAPER PATTERN:

Maximum Marks: 100 Exam Duration: 3Hourrs.

Part A: 8 compulsory questions.

One question from each module of Modules I - IV; and two each from Module V & VI.

Student has to answer all questions. (8 x5)=40

Part B: 3 questions uniformly covering Modules I & II. Student has to answer any 2 from the 3 questions: (2 x 10) =20. Each question can have maximum of 4 sub questions (a,b,c,d), if needed.

Part C: 3 questions uniformly covering Modules III & IV. Student has to answer any 2 from the 3 questions: (2 x 10) =20. Each question can have maximum of 4 sub questions (a,b,c,d), if needed.

Part D: 3 questions uniformly covering Modules V & VI. Student has to answer any 2 from the 3 questions: (2 x 10) =20. Each question can have maximum of 4 sub questions (a,b,c,d), if needed.

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SUB CODE: EE402

SUB NAME: SPECIAL ELECTRICAL MACHINES

SEM/YEAR: S8/IV

CONTENT BEYOND SYLLABUS

Synchronous Reluctance motors: Constructional features–Types–Axial& Radial Flux motors- closed loop control of SRM-Permanent magnet synchronous motors-ideal PMSM-armature reaction-power controllers-volt ampere requirements

NAME & SIGN OF FACULTY

(P.SUNDARAMOORTHI)

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QUESTION BANK- MODULE – I

1) Enumerate the importance of Drag Cup Servomotor.
2) List the applications of servomotors
3) With relevant diagram explain armature controlled DC servomotors
4) Compare the performance of AC&DC servomotors and list the applications
5) Justify the performance characteristics of AC Servomotor
6) List the applications of damped AC servomotors.
7) With relevant diagram explain field controlled DC servomotors
8) Describe the operating principles of series split field dc servomotors?

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QUESTION BANK- MODULE – II

1) Categorize any two driver circuits for a stepper motor
2) Explain the constructional details and working principles of permanent magnet stepper motor With neat sketches
3) Discuss the static performance characteristics of stepper motor
4) Define step angle and detent torque for a stepper motor
5) With neat sketches, explain the constructional details and working principles of variable reluctance stepper motor
6) With neat sketches, explain the constructional details and working principles of hybrid stepper motor
7) Define the terms of start-stop mode and slewing mode of stepper motor
8) Explain in detail about theory and operation of monofilar &bifilar windings in stepper motor

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QUESTION BANK- MODULE – III

1) List the merits and limitations of Universal motors
2) Explain the operating principles of AC series motor with neat sketch
3) Draw the phasor diagram of AC series motor and derive the voltage equation
4) Derive the torque equation of hysteresis motor
5) List the applications, merits and demerits of Universal motors
6) Draw the torque – slip characteristics of Hysteresis motors
7) Discuss the basic operating principles of Universal motor
8) Draw the torque-slip characteristics of AC series motor with neat sketch

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QUESTION BANK- MODULE – IV

1) Derive the torque equation of Reluctance motors
2) With neat sketches explain the construction and operation of 6/4 SRM
3) Explain the torque slip characteristics of Reluctance motor with necessary diagrams
4) Explain why rotor position required for the operation of switched reluctance motor
5) With neat sketches explain the construction and operation of 8/6 SRM
6) Explain the torque speed characteristics of SRM with necessary diagrams.
7) Describe in details about power converter circuits application in SRM
8) Explain in detail about different types of SRM.

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QUESTION BANK- MODULE – V

1) Compare mechanical commutation and electronic commutation
2) Differentiate trapezoidal type BLDC motor and sinusoidal type BLDC motor
3) Explain the principle of operation of PMBLDC motor for 180 degree commutation with neat diagram
4) Draw and explain the performance characteristics of PMBLDC motor
5) Examine the operating principles of PMDC motors
6) Give some applications of brushless dc motor with different types
7) Explain the principle of operation of PMBLDC motor for 120 degree commutation with neat diagram?
8) Write few applications of trapezoidal & sinusoidal type BLDC motors.

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QUESTION BANK- MODULE – VI

1) Enumerate linear motors and list any four applications
2) Write short note on linear synchronous motor.
3) With necessary diagram explain longitudinal flux linear switched reluctance motor and transverse flux linear switched reluctance motor
4) Derive the expression for linear force
5) Discuss in details about linear motors with different types
6) Draw the equivalent circuits of linear induction motors
7) With necessary diagram explain the construction, operating principles of linear induction motors
8) List the applications of linear motors

Module 1

AC and DC Servomotor

SERVOMOTOR

Ques 1) What do you mean by servomotor? Explain the construction and working principle of servomotor.

Ans: Servomotors

A servomotor is a low-power motor used in servomechanisms or position-control systems. A servomotor should have a good starting torque. It also should have quick acceleration at starting. To achieve this, the rotor is designed to have very low inertia and for this the ratio of its diameter to length is made small. It also needs to have linear torque-speed characteristics.

A servo motor is an electrical device which can push or rotate an object with great precision. If you want to rotate and object at some specific angles or distance, then you use servo motor. It is just made up of simple motor which run through servo mechanism. If motor is used is DC powered then it is called DC servo motor, and if it is AC powered motor then it is called AC servo motor. We can get a very high torque servo motor in a small and light weight packages. Doe to these features they are being used in many applications like toy car, RC helicopters and planes, Robotics, Machine etc.

Construction of Servo Motor

Servo motor is DC motor which consists of following parts:

1) **Stator Winding:** From the position of the rotor, a rotating magnetic field is created to efficiently generate torque.
2) **Rotor Winding:** A high function rare earth or other permanent magnet is positioned externally to the shaft.
3) **Bearing:** Ball Bearing
4) **Shaft:** This part transmits the motor output power. The load is driven through the transfer mechanism (such as the coupling).
5) **Encoder:** The optical encoder always watches the number of rotations and the position of the shaft.
6) **Winding:** Current flows in the winding to create a rotating magnetic field.

The servo motor consists of two winding stator and rotor winding. The stator winding is wound on stationary part of the motor and this winding is also called field winding of the motor, this winding could the permanent magnets. The rotor winding is wound on the rotating part of the motor and this winding is also called the armature winding of the motor. The motor consists of two bearing on front and back side for the free movement of shaft. Shaft is basically the iron rod on which the armature winding is coupled. The encoder has the approximate sensor for telling the rotational speed and revolution per minute of the motor. The construction of servo motor is shown in **figure 1.1**

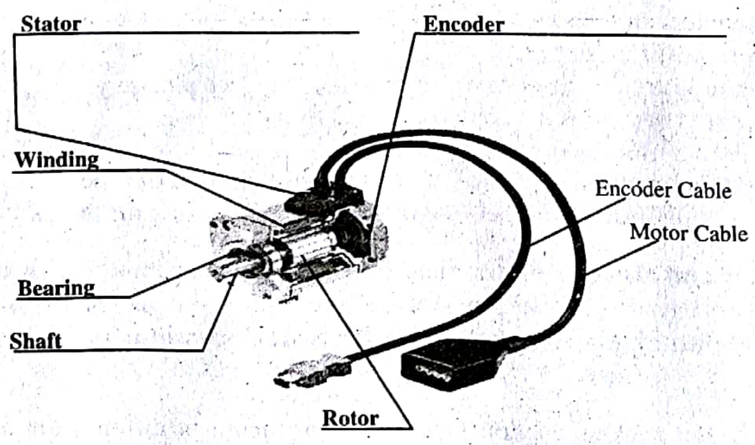


Figure 1.1

Working Principle of Servo Motors

A servo consists of a Motor (DC or AC), a potentiometer, gear assembly and a controlling circuit. First of all we use gear assembly to reduce RPM and to increase torque of motor. Say at initial position of servo motor shaft, the position of the potentiometer knob is such that there is no electrical signal generated at the output port of the potentiometer. Now an electrical signal is given to another input terminal of the error detector amplifier. Now difference between these two signals, one comes from potentiometer and another comes from other source, will be processed in feedback mechanism and output will be provided in term of error signal. This error signal acts as the input for motor and motor starts rotating.

Now motor shaft is connected with potentiometer and as motor rotates so the potentiometer and it will generate a signal. So as the potentiometer's angular position changes, its output feedback signal changes, After sometime the position of potentiometer reaches at a position that the output of potentiometer is same as external signal provided. At this condition, there will be no output signal from the amplifier to the motor input as there is no difference between external applied signal and the signal generated at potentiometer, and in this situation motor stops rotating.

Ques 2) Describe the various types of servomotor and also write the applications of servomotor.

Ans: Types of Servomotor

The various types of servomotor are explained as follows:

1) **DC Servomotor:** A DC servomotor is essentially an ordinary DC motor with an armature and a field system. The field can be an electromagnetic type with a field winding wound around a salient pole and excited with a DC current. It can also be a permanent magnet type. Servomotors are generally operated at low speeds.

2) **AC Servomotor:** Most of the servomotors used in the low power servomechanism are AC servomotors. The AC servomotor is basically two phase induction motor. The output power of AC servomotor varies from fraction of watts to few hundred of watts. The operating frequency is 50 Hz to 400 Hz.

3) **Positional Rotation Servo Motor:** Positional rotation servo motor is a most common type of servo motor. The shaft's o/p rotates in about 180°. It includes physical stops located in the gear mechanism to stop turning outside these limits to guard the rotation sensor. These common servos involve in radio controlled water, radio controlled cars, aircraft, robots, toys and many other applications.

4) **Continuous Rotation Servo Motor:** Continuous rotation servo motor is quite related to the common positional rotation servo motor, but it can go in any direction indefinitely. The control signal, rather than set the static position of the servo, is understood as the speed and direction of rotation. The range of potential commands sources the servo to rotate clockwise or anticlockwise as preferred, at changing speed, depending on the command signal. This type of motor is used in a radar dish if you are riding one on a robot or you can use one as a drive motor on a mobile robot.

5) **Linear Servo Motor:** Linear servo motor is also similar the positional rotation servo motor is discussed above, but with an extra gears to alter the o/p from circular to back-and-forth. These servo motors are not simple to find, but sometimes you can find them at hobby stores where they are used as actuators in higher model airplanes.

Applications of the Servo Motor

The power rating of the servo motor may vary from the fraction of watts to few hundreds of watts. The rotors of servo motor have low inertia strength, and therefore they have a high speed of inertia. The Applications of the Servomotor are as follows:

1) They are used in Radar system and process controller.
2) Servomotors are used in computers and robotics.
3) It is used in robotic industry of position control.
4) It is used in press and cutting industry for the cutting and pressing the piece precisely.
5) It is used in conveyer belt for start and stops the conveyer belt at every position.
6) It is used in digital cameras for auto focusing.
7) It is used in solar tracking system for tracking the sun at every precise moment of time.
8) It is used in labelling and packing industry for labels the monogram and packing the things.

Ques 3) Explain AC servomotor and also explain the construction of AC servomotor with suitable diagram.

Or

Explain the principle of operation of A.C. servomotor with neat diagram.

Ans: AC Servomotor

An AC servomotor is basically a two-phase induction motor. In construction it differs from a normal induction motor because of certain special design features. AC servo motors are basically two-phase squirrel cage induction motors and are used for low power applications. Nowadays, three phase squirrel cage induction motors have been modified such that they can be used in high power servo systems.

The main difference between a standard split-phase induction motor and AC motor is that the squirrel cage rotor of a servo motor has made with thinner conducting bars, so that the motor resistance is higher.

Construction of AC Servomotor

The AC servomotor is basically consists of a stator and a rotor. The stator carries two windings, uniformly distributed and displaced by 90° in space, from each other. On winding is called as main winding or fixed winding or reference winding. The reference winding is excited by a constant voltage AC supply. The other winding is called as control winding. It is excited by variable control voltage, which is obtained from a servo amplifier. The winding are 90° away from each other and control voltage is 90° out of phase with respect to the voltage applied to the reference winding. This is necessary to obtain rotating magnetic field.

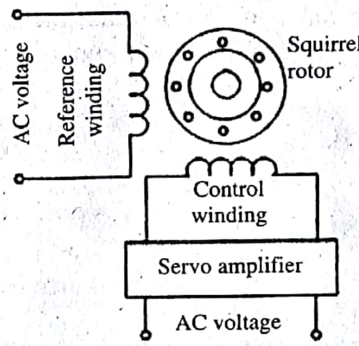


Figure 1.2: AC Servomotor

Principle of Operation of AC Servo Motor

The schematic diagram of servo system for AC two-phase induction motor is shown in the **figure 1.3**. In this, the reference input at which the motor shaft has to maintain at a certain position is given to the rotor of synchro generator as mechanical input θ. This rotor is connected to the electrical input at rated voltage at a fixed frequency.

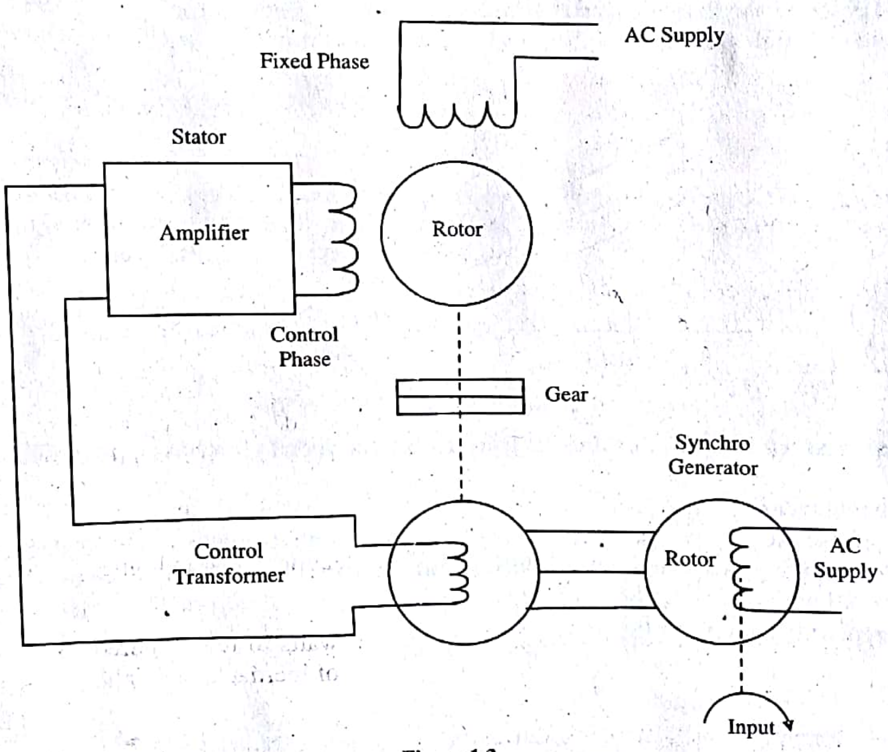


Figure 1.3

The three stator terminals of a synchro generator are connected correspondingly to the terminals of control transformer. The angular position of the two-phase motor is transmitted to the rotor of control transformer through gear train arrangement and it represents the control condition alpha.

Initially, there exist a difference between the synchro generator shaft position and control transformer shaft position. This error is reflected as the voltage across the control transformer. This error voltage is applied to the servo amplifier and then to the control p

hase of the motor. With the control voltage, the rotor of the motor rotates in required direction till the error becomes zero. This is how the desired shaft position is ensured in AC servo motors. Alternatively, modern AC servo drives are embedded controllers like PLCs, microprocessors and microcontrollers to achieve variable frequency and variable voltage in order to drive the motor.

Mostly, pulse width modulation and Proportional-Integral-Derivative (PID) techniques are used to control the desired frequency and voltage. The block diagram of AC servo motor system using programmable logic controllers, position and servo controllers is shown in **figure 1.4**.

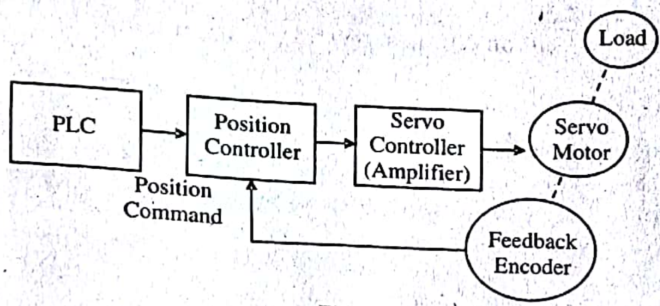


Figure 1.4

Ques 4) Explain the performance characteristics of AC servomotor with suitable diagram.

Ans: Performance Characteristics of AC Servomotor

In a normal induction motor, the torque-speed characteristics have both a positive slope region (unstable region) and a negative slope region (stable region). For an AC servomotor, the torque-slip characteristics should not have a positive slip region to ensure stability. Moreover, the torque developed should linearly decrease with speed. For these two reasons, the value of the rotor circuit resistance of an AC servomotor must be high. The servomotor should also have quick acceleration from standstill. Hence the rotor should have low inertia. For this reason, the rotor is constructed with a smaller diameter-to-length ratio. **Figure 1.5** shows the torque **speed characteristics of AC servomotor.**

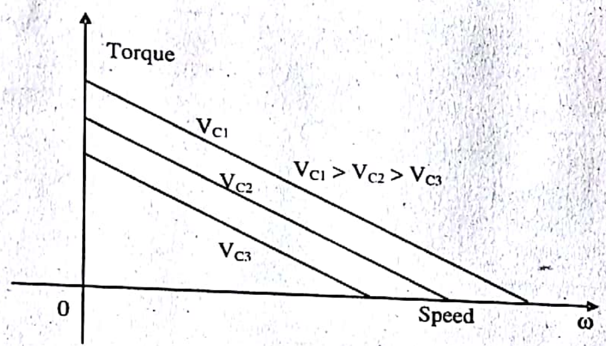


Figure 1.5: Characteristics of AC Servomotor

Ques 5) Explain Damped AC servomotor and also sketch torque speed characteristic of Damped AC servomotor

Ans: Damped AC Servomotor

The stator of the two-phase AC Servomotor has the two distributed windings which are displaced from each other by 90 degrees electrical. One winding is known as a **Reference or Fixed Phase**, which is supplied from a constant voltage source. The other one is known as **Control Phase**, and the connection diagram of Damped AC Servomotor is shown in **figure 1.6**. It is provided with a variable voltage.

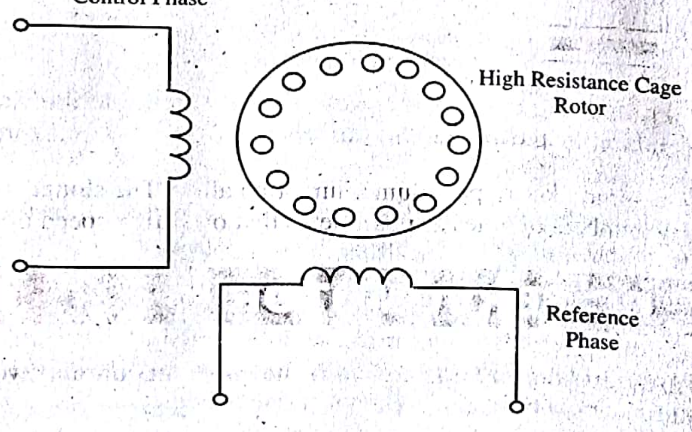


Figure 1.6

The control phase is usually supplied from a servo amplifier. The speed and torque of the rotor are controlled by the phase difference between the control voltage and the reference phase voltage. By reversing the phase difference from leading to lagging or vice versa, the direction of the rotation of the rotor can be reversed.

Torque Speed Characteristic of Damped AC Servomotor

The torque speed characteristic of Damped AC servomotor is shown in the **figure 1.7**:

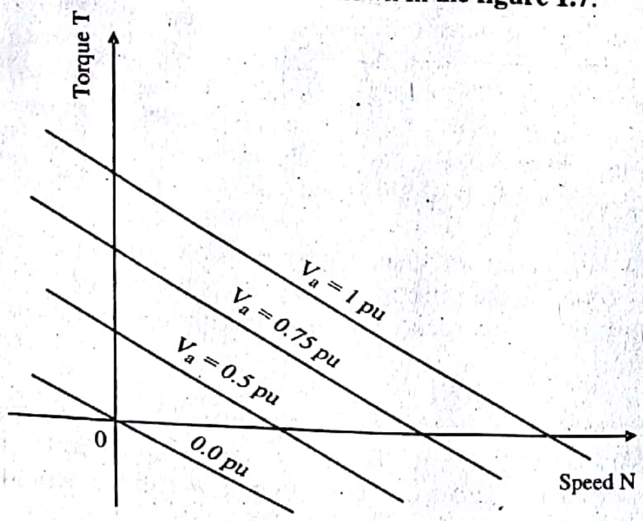


Figure 1.7

The negative slope represents a high rotor resistance and provides the motor with positive damping for better stability.

Ques 6) Write short note on AC drag cup servomotor.

Ans: Drag-Cup Rotor Servomotor

Drag-cup construction is used for very low inertia, in this type of motor, the rotor construction is usually of squirrel cage or drag-cup type; here only a light cup rotates while the rotor core is stationary (thus inertia is quite small).

The servo-motors contains two windings namely, main winding (sometimes called fixed or reference winding) and control winding. The voltages applied to-the windings are at right angles to one another.

Usually one winding is excited with a fixed voltage while the other one is excited by the control voltage {which is the output from servo-amplifier}. While in operation, the output torque of the motor is roughly proportional to the applied control voltage, and the direction of torque is determined by the polarity of the control voltage.

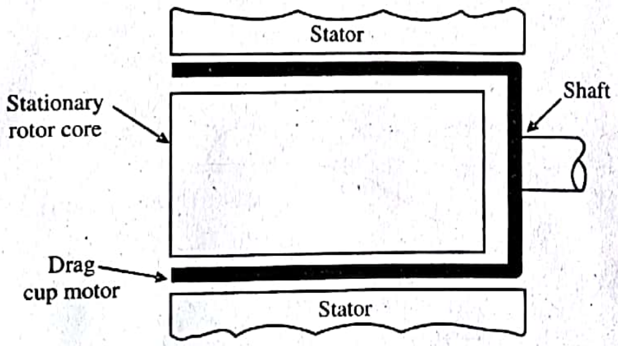


Figure 1.8: Drag-Cup Rotor Servomotor

The drag cup is made up of nonmagnetic material like copper, aluminium or an alloy. The slotted rotor laminations in this construction. These are wound for as many numbers of poles as possible so that operating speed of motor is very low.

DC SERVOMOTOR

Ques 7) What do you understand by DC servomotor? Also explain the construction and working principle of DC servomotor.

Ans: DC Servomotor

The motor which is used as a DC servo motor generally have a separate DC source in the field of winding & armature winding. The control can be archived either by controlling the armature current or field current. Field control includes some particular advantages over armature control. In the same way armature control includes some advantages over field control. Based on the applications the control should be applied to the DC servo motor. DC servo motor provides very accurate and also fast respond to start or stop command signals due to the low armature inductive reactance. DC servo motors are used in similar equipment and computerized numerically controlled machines.

Construction of DC Servo Motors

A DC servo motor consists of a small DC motor, feedback potentiometer, gearbox, motor drive electronic circuit and electronic feedback control loop. It is more or less similar to the normal DC motor. The stator of the motor consists of a cylindrical frame and the magnet is attached to the inside of the frame.

The rotor consists of brush and shaft. A commutator and a rotor metal supporting frame are attached to the outside of the shaft and the armature winding is coiled in the rotor metal supporting frame. A brush is built with an armature coil that supplies the current to the commutator. At the back of the shaft, a detector is built into the rotor in order to detect the rotation speed.

With this construction, it is simple to design a controller using simple circuitry because the torque is proportional to the amount of current flow through the armature. And also the instantaneous polarity of the control voltage decides the direction of torque developed by the motor. Types of DC servo motors include series motors, shunt control motor, split series motor, and permanent magnet shunt motor.

Working Principle of DC Servo Motor

A DC servo motor is an assembly of four major components, namely a DC motor, a position sensing device, a gear assembly, and a control circuit. The **figure 1.9** shows the parts that consisting in RC servo motors in which small DC motor is employed for driving the loads at precise speed and position.

A DC reference voltage is set to the value corresponding to the desired output. This voltage can be applied by using another potentiometer, control pulse width to voltage converter, or through timers depending on the control circuitry. The dial on the potentiometer produces a corresponding voltage which is then applied as one of the inputs to error amplifier.

In some circuits, a control pulse is used to produce DC reference voltage corresponding to desired position or speed of the motor and it is applied to a pulse width to voltage converter. In this converter, the capacitor starts charging at a constant rate when the pulse high. Then the charge on the capacitor is fed to the buffer amplifier when the pulse is low and this charge is further applied to the error amplifier.

So the length of the pulse decides the voltage applied at the error amplifier as a desired voltage to produce the desired speed or position. In digital control, microprocessor or microcontroller are used for generating the PWM pluses in terms of duty cycles to produce more accurate control signals.

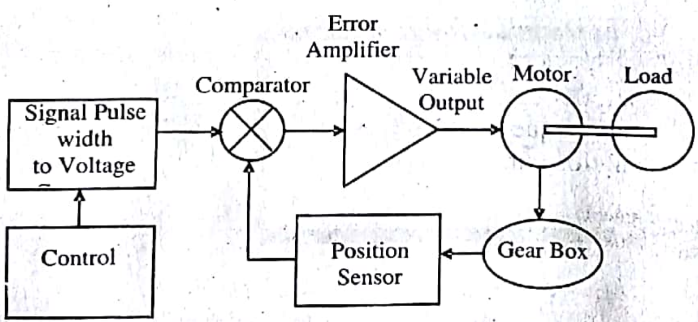


Figure 1.9

The feedback signal corresponding to the present position of the load is obtained by using a position sensor. This sensor is normally a potentiometer that produces the voltage corresponding to the absolute angle of the motor shaft through gear mechanism. Then the feedback voltage value is applied at the input of error amplifier (comparator).

The error amplifier is a negative feedback amplifier and it reduces the difference between its inputs. It compares the voltage related to current position of the motor (obtained by potentiometer) with desired voltage related to desired position of the motor (obtained by pulse width to voltage converter), and produces the error either a positive or negative voltage.

This error voltage is applied to the armature of the motor. If the error is more, the more output is applied to the motor armature. As long as error exists, the amplifier amplifies the error voltage and correspondingly powers the armature. The motor rotates till the error becomes zero. If the error is negative, the armature voltage reverses and hence the armature rotates in the opposite direction.

Ques 8) Explain field controlled DC servomotors also explain its operation and sketch characteristics diagram.

Ans: Field Controlled DC Servo Motor

The **figure 1.10** illustrates the schematic diagram for a field controlled DC servo motor. In this arrangement, the field of DC motor is excited be the amplified error signal and armature winding is energised by a constant current source.

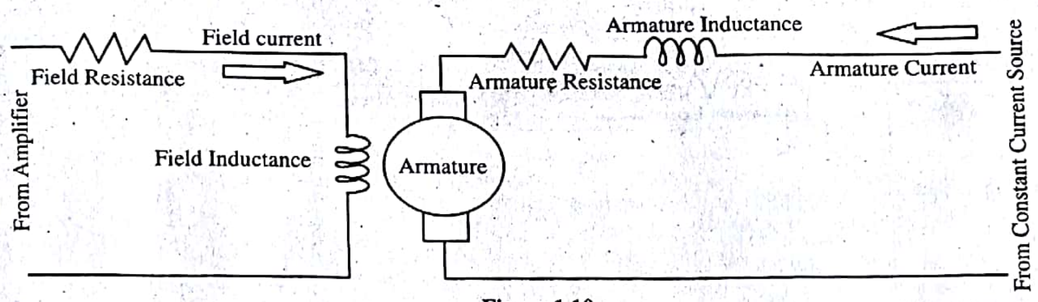


Figure 1.10

Operation

As field of this DC servomotor is excited by amplified error signal, the torque of the motor, i.e., rotation of the motor can be controlled by amplified error signal. If the constant armature current is large enough then, every little change in field current causes corresponding change in torque on the motor shaft.

The direction of rotation can be changed by changing polarity of the field. The direction of rotation can also be altered by using split field DC motor, where the field winding is divided into two parts, one half of the winding is wound in clockwise direction and other half in wound in anticlockwise direction. The amplified error signal is fed to the junction point of these two halves of the field as shown in **figure 1.10** . The magnetic field of both halves of the field winding opposes each other.

During operation of the motor, magnetic field strength of one half dominates other depending upon the value of amplified error signal fed between these halves. Due to this, the DC servomotor rotates in a particular direction according to the amplified error signal voltage. The main disadvantage of field control DC servomotors is that the dynamic response to the error is slower because of longer time constant of inductive field circuit.

The field is an electromagnet so it is basically a highly inductive circuit hence due to sudden change in error signal voltage, the current through the field will reach to its steady state value after certain period depending upon the time constant of the field circuit. That is why field control DC servo motor arrangement is mainly used in small servo motor applications. The main advantage of using field control scheme is that, as the motor is controlled by field – the controlling power requirement is much lower than rated power of the motor.

Characteristics of Field Controlled DC Servo Motor

The field is controlled below the knee point of magnetising saturation curve. At that portion of the curve the mmf linearly varies with excitation current. That means torque developed in the DC motor is directly proportional to the field current below the knee point of magnetising saturation curve.

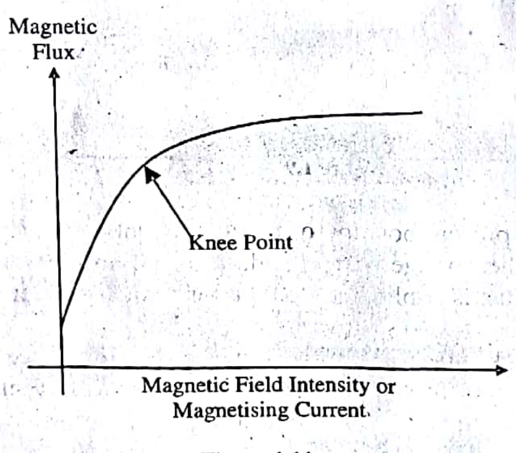


Figure 1.11

From general torque equation of DC motor it is found that, torque $T \propto \phi I_a$. Where, φ is field flux and Ia is armature current. But in field controlled DC servomotor, the armature is excited by constant current source, hence Ia is constant here. Hence, $T \propto \phi$.

Ques 9) Discuss about the Armature controlled DC servomotors also discuss its operation with suitable diagram. Also sketch its characteristics graph.

Ans: Armature Controlled DC Servo Motor

The **figure 1.12** shows the schematic diagram for an armature controlled DC servo motor. Here the armature is energised by amplified error signal and field is excited by a constant current source.

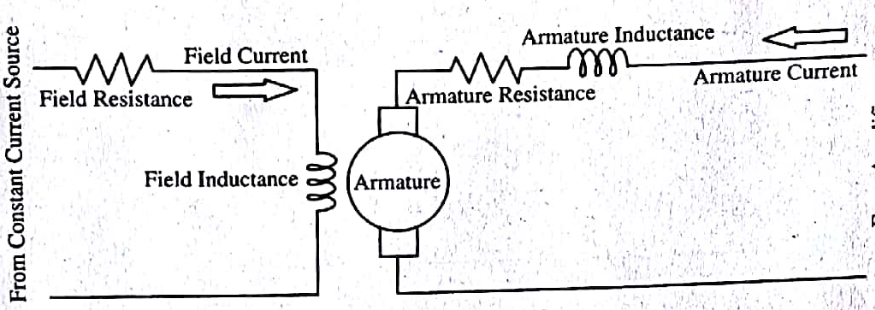


Figure 1.12

Operation

The field is operated at well beyond the knee point of magnetising saturation curve. In this portion of the curve, for huge change in magnetising current, there is very small change in mmf in the motor field. This makes the servo motor is less sensitive to change in field current. Actually for armature controlled DC servo motor, we do not want that, the motor should response to any change of field current.

Again, at saturation the field flux is maximum. As we said earlier, the general torque equation of DC motor is, torque $T \propto \phi I_a$. Now if ϕ is large enough, for every little change in armature current Ia there will be a prominent changer in motor torque. That means servo motor becomes much sensitive to the armature current.

As the armature of DC motor is less inductive and more resistive, time constant of armature winding is small enough. This causes quick change of armature current due to sudden change in armature voltage. That is why dynamic response of armature controlled DC servo motor is much faster than that of field controlled DC servo motor. The direction of rotation of the motor can easily be changed by reversing the polarity of the error signal.

Characteristics of Armature Controlled DC Servomotor

The characteristics of armature controlled DC servomotor are shown in **figure 1.13:**

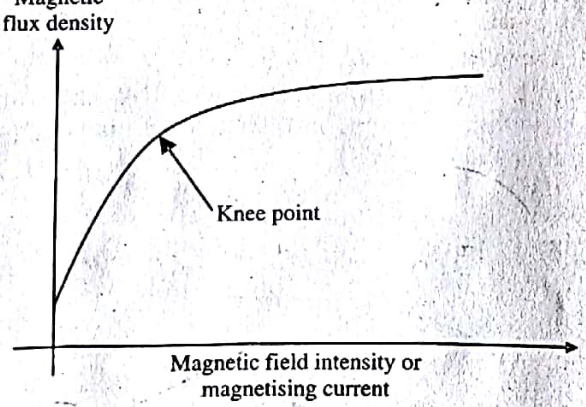


Figure 1.13

Ques 10) Write a short note on:

i) **Permanent Magnet armature controlled DC servomotor**

ii) **Series Split Field DC Servomotor**

Ans: Permanent-Magnet Armature-Controlled DC Servomotor

It is usually manufactured in 6V and 28V ratings in fractional-horsepower sizes and in 150V ratings in integral-horsepower sizes up to 2 hp. The field structure for this type of motor usually consists of Alnico VI alloy, cast in the form of a circular ring, completely surrounding the armature and providing a strong, constant flux.

The permanent-magnet motors are well compensated by means of commutating windings to avoid demagnetisation of the field magnets whenever the dc armature voltage is suddenly reversed. Eddy currents and hysteresis effects in these motors are generally negligible, and the pole pieces are usually laminated to reduce arcing at brushes whenever a rapid change of signal voltage occurs.

These devices are also controlled by armature voltage control in the same manner as the armature-controlled shunt motor.

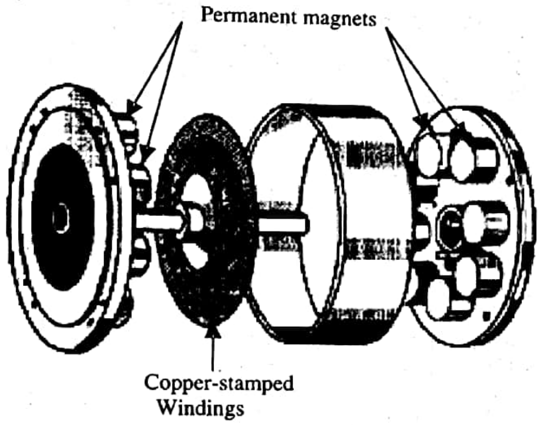


Figure 1.14

Series Split Field DC Servomotor

Split series motor is the DC series motor with split-field rated with some fractional kilowatt. This type of motor can operate as a separately excited field-controlled motor. The armature is supplied with a constant current source. Split series motor has a typical torque-speed curve. This curve denotes high stall torque and a rapid reduction in torque with increase in speed. This results in good damping.

They are the motors with split-field rate with some fractional kilowatts. Split series motor has a typical torque-speed curve. This curve denotes high stall torque and a rapid reduction in torque with high speed.

The DC series motor with split field (small fractional kW) may be operated as a separately excited field-controlled motor (**figure 1.15**).

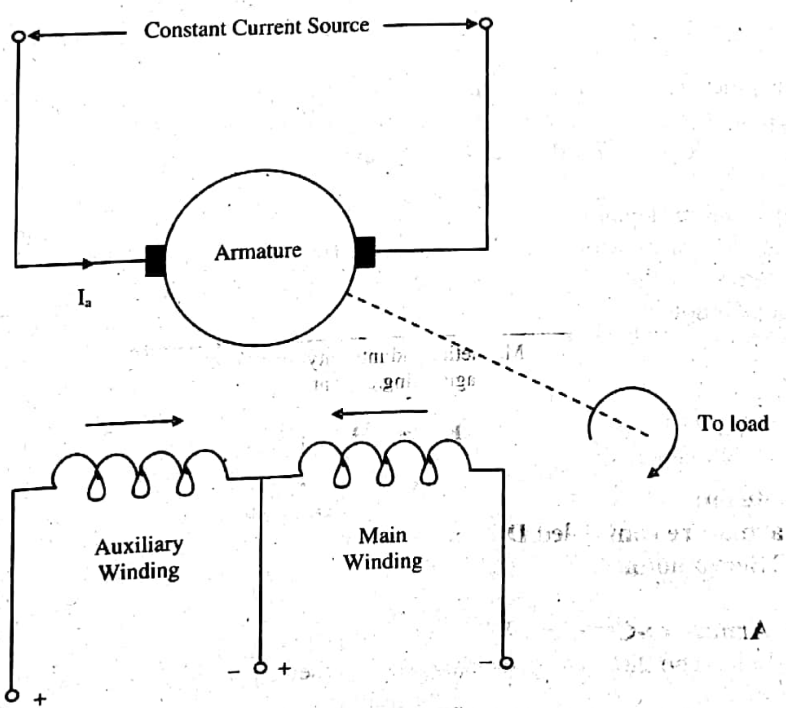


Figure 1.15: From-D.C. Amplifier

Module 2

Stepper Motor

STEPPER MOTOR

Ques 1) What do you mean by Stepper Motor? Explain construction and working principle of stepper motor. Write the different types of stepper motor.

Ans: Stepper Motor
A stepper motor is an electromechanical device which actuates a train of step angular (or linear) movement in response to a train of input pulses on one-to-one basis, i.e., one step actuation movement for each pulse input. A stepper motor is the actuator element of incremental motion control system. Stepper motors are used for computer peripherals like printers, tape drives, capstan drive, machine tool and process control system.

The step size of the stepper motor is given by $\alpha = \left(\frac{360}{nT}\right)$ where, n is number of stakes and T is number of teeth of rotor.

Construction and Working Principle
Stepper Motor is a brushless electromechanical device which converts the train of electric pulses applied at their excitation windings into precisely defined step-by-step mechanical shaft rotation. The shaft of the motor rotates through a fixed angle for each discrete pulse. This rotation can be linear or angular. It gets one step movement for a single pulse input.

When a train of pulses is applied, it gets turned through a certain angle. The angle through which the stepper motor shaft turns for each pulse is referred as the step angle, which is generally expressed in degrees.

The number of input pulses given to the motor decides the step angle and hence the position of motor shaft is controlled by controlling the number of pulses. This unique feature makes the stepper motor to be well suitable for open-loop control system wherein the precise position of the shaft is maintained with exact number of pulses without using a feedback sensor.

If the step angle is smaller, the greater will be the number of steps per revolutions and higher will be the accuracy of the position obtained. The step angles can be as large as 90 degrees and as small as 0.72 degrees, however, the commonly used step angles are 1.8 degrees, 2.5 degrees, 7.5 degrees and 15 degrees.

The direction of the shaft rotation depends on the sequence of pulses applied to the stator. The speed of the shaft or the average motor speed is directly proportional to the frequency (the rate of input pulses) of input pulses being applied at excitation windings. Therefore, if the frequency is low, the stepper motor rotates in steps and for high frequency, it continuously rotates like a DC motor due to inertia.

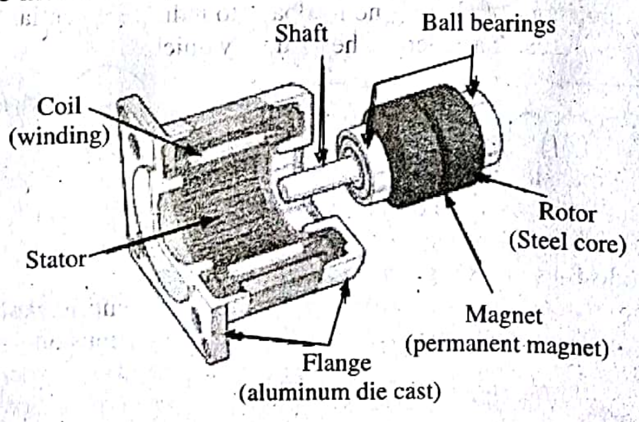


Figure: 2.1 Construction of Stepper Motor

Like all electric motors, it has stator and rotor. The rotor is the movable part which has no windings, brushes and a commutator. Usually the rotors are either variable reluctance or permanent magnet kind. The stator is often constructed with multipole and multiphase windings, usually of three or four phase windings wound for a required number of poles decided by desired angular displacement per input pulse. Unlike other motors it operates on a programmed discrete control pulses that are applied to the stator windings via an electronic drive. The rotation occurs due to the magnetic interaction between poles of sequentially energized stator winding and poles of the rotor.

Types of Stepper Motor

The **types of stepper motors** based on maximum usage include:

1) **Permanent Magnet Stepper Motor:** Permanent magnet motors use a permanent magnet (PM) in the rotor and operate on the attraction or repulsion between the rotor PM and the stator electromagnets.
2) **Variable Reluctance Stepper Motor:** Variable reluctance (VR) motors have a plain iron rotor and operate based on the principle that minimum reluctance occurs with minimum gap, hence the rotor points are attracted toward the stator magnet poles.
3) **Hybrid Synchronous Stepper Motor:** Hybrid stepper motors are named because they use a combination of permanent magnet (PM) and variable reluctance (VR) techniques to achieve maximum power in a small package size.

Ques 2) Write the selection criteria of stepper motor.

Ans: Selection of Motor

Stepper motor can be selected based on the following specifications as explained as:

1) Electrical specifications include number of phases, step angle, winding voltage, winding resistance/inductance, holding torque, pull-out torque, maximum slew rate, positional accuracy, temperature rise and power supply and drive circuits.
2) Mechanical specifications includes shaft length and shape, motor length, shape of flange face, lead wire length and connector type.

Ques 3) Write the advantages, disadvantages and application of stepper motor

Ans: Advantages of Stepper Motor

1) At standstill position, the motor has full torque.
2) It has a good response to starting, stopping and reversing position.
3) As there is no contact brushes in the stepper motor, it is reliable and the life expectancy depends on the bearings of the motor.
4) The motor rotation angle is directly proportional to the input signals.
5) It is simple and less costly to control as motor provides open loop control when responding to the digital input signals.
6) The motor speed is directly proportional to the input pulses frequency, this way a wide range of rotational speed can be achieved.
7) When load is coupled to the shaft, it is still possible to realise the synchronous rotation with low speed.
8) The exact positioning and repeatability of movement is good as it has a 3-5% accuracy of a step where the error is non-cumulative from one step to another.
9) Stepper motors are safer and low cost (as compared to servo motors), having high torque at low speeds, high reliability with simple construction which operates at any environment.

Disadvantages of Stepper Motors

1) Stepper motors having low Efficiency.
2) It has low Accuracy.
3) Its torque declines very quickly with speed.
4) As stepper motor operates in open loop control, there is no feedback to indicate potential missed steps.
5) It has low torque to inertia ratio means it can't accelerate the load very quickly.
6) They are noisy.

Applications of Stepper Motor

1) They are used in numeric control of machine tools.
2) Used in tape drives, floppy disc drives, printers and electric watches.
3) The stepper motor also use in X-Y plotter and robotics.
4) It has wide application in textile industries and integrated circuit fabrications.
5) The other applications of the Stepper Motor are in spacecrafts launched for scientific explorations of the planets, etc.
6) These motors also find a variety of commercial, medical and military applications and also used in the production of science fiction movies.
7) Stepper motors of microwatts are used in the wrist watches.
8) In the machine tool, the stepper motors with ratings of several tens of kilowatts is used.

Ques 4) Explain the variable reluctance stepper motor and explain the theory of operation with suitable diagram.

Ans: Variable Reluctance Stepper Motor

The principle of Variable Reluctance Stepper motor is based on the property of the flux lines which capture the low reluctance path. The stator and the rotor of the motor are aligned in such a way that the magnetic reluctance is minimum.

Variable reluctance stepper motors have the simplest design of the three types, with a soft iron, non-magnetic, toothed rotor and a wound, electromagnetic stator. Because the rotor is not magnetized, there's no attraction between the rotor and stator when the windings aren't energized, so variable reluctance motors don't produce detent torque.

Working of a Variable Reluctance Stepper Motor

A four phase or (4/2 pole), single stack variable reluctance stepper motor is shown in **figure 2.2.** Here, (4/2 pole) means that the stator has four poles and the rotor has two poles.

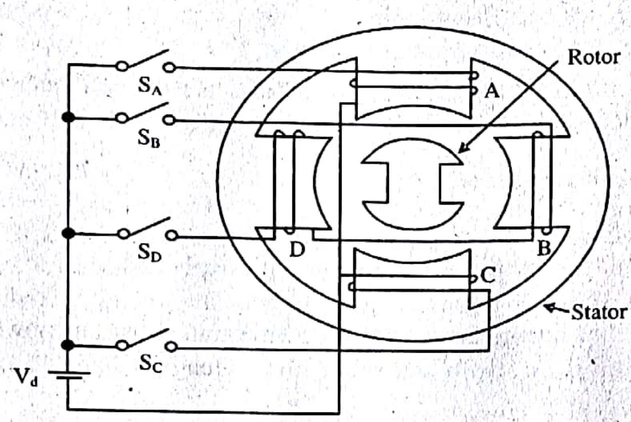


Figure 2.2

The four phases A, B, C and D are connected to the DC source with the help of a semiconductor, switches S_A, S_B, S_C and S_D respectively as shown in the above figure. The phase windings of the stator are energised in the sequence A, B, C, D, A. The rotor aligns itself with the axis of phase A as the winding A is energised. The rotor is stable in this position and cannot move until phase A is de-energised.

Now, the phase B is excited and phase A is disconnected. The rotor moves 90 degrees in the clockwise direction to align with the resultant air gap field which lies along the axis of phase B. Similarly the phase C is energised, and the phase B is disconnected, and the rotor moves again in 90 degrees to align itself with the axis of the phase.

Thus, as the Phases are excited in the order as A, B, C, D, A, the rotor moves 90 degrees at each transition step in the clockwise direction. The rotor completes one revolution in 4 steps. The direction of the rotation depends on the sequence of switching the phase and does not depend on the direction of the current flowing through the phase. Thus, the direction can be reversed by changing the phase sequence like A, D, C, B, A.

The magnitude of the step angle of the variable reluctance motor is given as,

$$\alpha = \frac{360°}{m_s N_r}$$

Where,
α is the step angle
ms is the number of stator phases
Nr is the number of rotor teeth

The step angle is expressed as shown below,

$$\alpha = \frac{N_s - N_r}{N_s N_r} x\, 360°$$

Where, N_S is the stator poles

The step angle can be reduced from 90 degrees to 45 degrees in a clockwise direction by exciting the phase in the sequence A, A + B, B, B + C, C, C + D, D, D + A, A.

Similarly, if the sequence is reversed as A, A + D, D, D + C, C, C + B, B, B + A, A, the rotor rotates at step angle of 45 degrees in the anticlockwise direction.

Here, (A + B) means that the phase windings A and B both are energised together. The resultant field is the midway of the two poles. That is it makes an angle of 45 degrees with the axis of the pole in the clockwise direction. This method of shifting excitation from one phase to another is known as Microstepping. By using Stepper Motor, lower values of the step angle can be obtained with numbers of poles on the stator.

Consider a 4 phase, (8/6 pole) single stack variable reluctance motor shown in the **figure 2.3**.

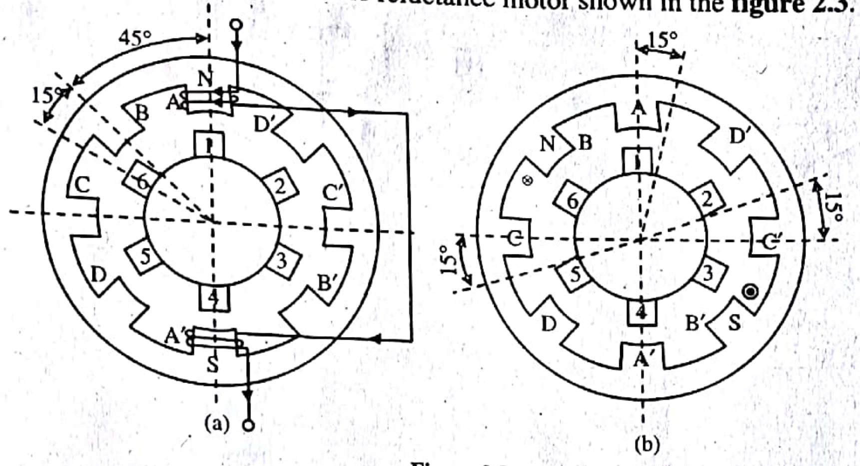


Figure 2.3

The opposite poles are connected in series forming a 4 phases. The rotor as 6 poles, when the coil AA′ is excited the rotor teeth 1 and 4 are aligned along the axis of the winding of the phase A. Thus, the rotor occupies the position as shown in the **figure 2.3**.

Now, the phase A is de-energised, and the phase winding B is energised. The rotor teeth 3 and 6 get aligned along the axis of phase B. The rotor moves a step of phase angle of 15 degrees in the clockwise direction. Further, the phase B is de-energised, and the winding C is excited. The rotor moves again 15° phase angle. The sequence A, B, C, D, A is followed, and the four steps of rotation are completed, and the rotor moves 60 degrees in clockwise direction. For one complete revolution of the rotor 24 steps are required. Thus, any desired step angle can be obtained by choosing different combinations of the number of rotor teeth and stator exciting coils.

Ques 5) What do you mean by permanent magnet stepper motor? Explain the theory of operation of permanent magnet stepper motor.

Ans: Permanent Magnet Stepper Motor

The Permanent Magnet Stepper Motor has a stator construction similar to that of the single stack variable reluctance motor. The rotor consists of permanent magnet poles of high retentively steel and is cylindrical in shape. The concentrating windings on diametrically opposite poles are connected in series to form a two phase winding on the stator. The rotor poles align with the stator teeth depending on the excitation of the winding. The two coils AA′ connected in series to form a winding of phase A. Similarly the two coil BB′ is connected in series forming a phase B windings. The **figure 2.4** shows 4/2 Pole Permanent Magnet Stepper Motor.

Theory of operation of Permanent Magnet Stepper Motor

In **figure 2.4 (a)** the current flows start to the end of phase A. The phase winding is denoted by A^+ and the current by i^+_A. The figure shows the condition when the phase winding is excited with the current i^+_A. The south pole of the rotor is attracted by the stator phase A. Thus, the magnetic axis of the stator and rotor coincide and $\alpha = 0°$.

Similarly, in the **figure 2.4 (b)** the current flows from the start to the end at phase B. The current is denoted by i^+_B and the winding by B^+. Considering the **figure 2.4 (b)**, the windings of phase A does not carry any current and the phase B is excited by the i^+_B current. The stator pole attracts the rotor pole and the rotor moves by 90° in the clockwise direction. Here $\alpha = 90°$.

The **figure 2.4 (c)** shows that the current flows from the end to the start of the phase A. This current is denoted by i^-_A and the winding is denoted by A^-. The current i^-_A is opposite to the current i^+_A. Here, phase B winding is de-energised and phase A winding is excited by the current i^-_A. The rotor moves further 90° in clockwise direction and the $\alpha = 180°$.

In the **figure 2.4 (d)**, the current flows from end to starting point of phase B. The current is represented by i^-_B and the winding by B^-. Phase A carries no current and the phase B is excited. The rotor again moves further 90° and the value of $\alpha = 270°$.

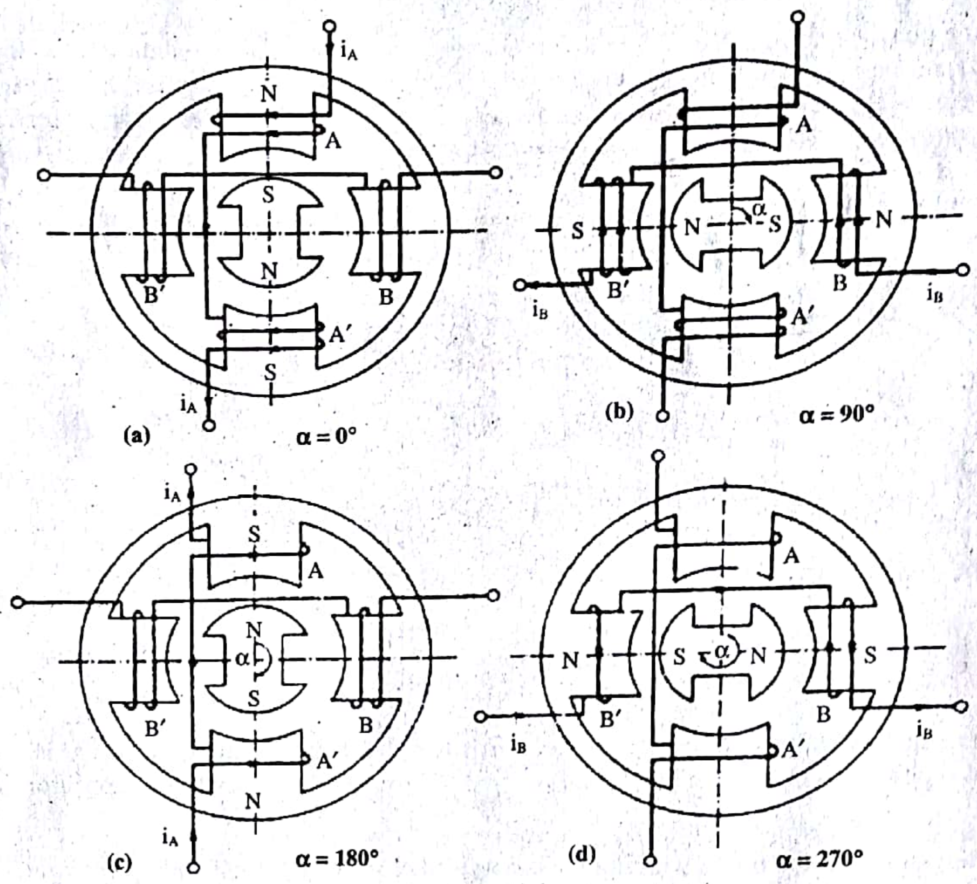


Figure 2.4

Completing the one revolution of the rotor for making α = 360° the rotor moves further 90 degrees by de-energising the winding of phase B and exciting the phase A. In the permanent magnet stepper motor the direction of the rotation depends on the polarity of the phase current. The sequence A^+, B^+, A^-, B^-, A^+ is followed by the clockwise movement of the rotor and for the anticlockwise movement, the sequence becomes A^+ B^-, A^-, B^+, A^+. The permanent magnet rotor with large number of poles is difficult to make, therefore, stepper motors of this type are restricted to large step size in the range of 30 to 90°. They have higher inertia and therefore, lower acceleration than variable stepper motors. The Permanent Magnet stepper motor produces more torque than the Variable Reluctance Stepper Motor.

Ques 6) What do you understand by hybrid type stepper motor? Explain the theory of operation of Hybrid type stepper motor.

Ans: Hybrid Type Stepper Motor

The word Hybrid means combination or mixture. The Hybrid Stepper Motor is a combination of the features of the Variable Reluctance Stepper Motor and Permanent Magnet Stepper Motor. In the centre of the rotor, an axial permanent magnet is provided. It is magnetised to produce a pair of poles as North (N) and South (S) as shown in the **figure 2.5.**

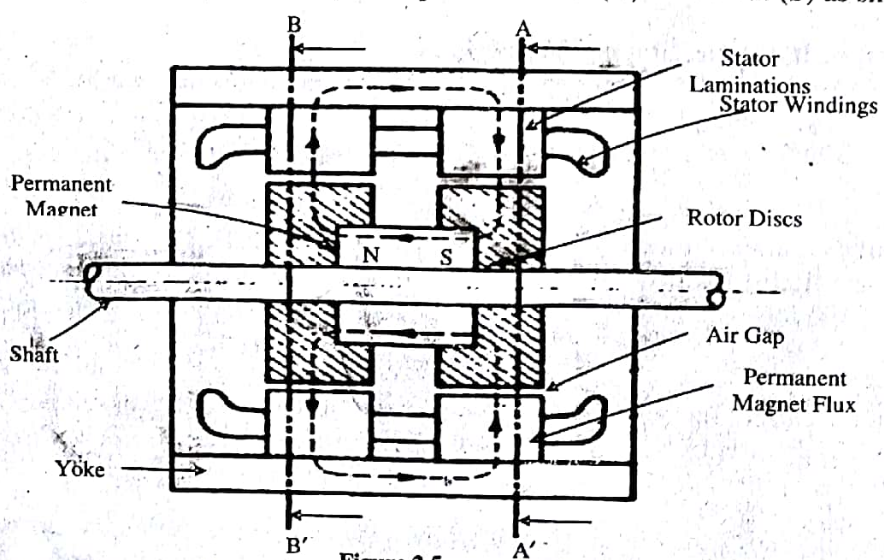


Figure 2.5

Theory of Operation of Hybrid Type Stepper Motor

At both the end of the axial magnet the end caps are provide, which contains an equal number of teeth which are magnetised by the magnet. The figure of the cross-section of the two end caps of the rotor is shown in **figure 2.6.**

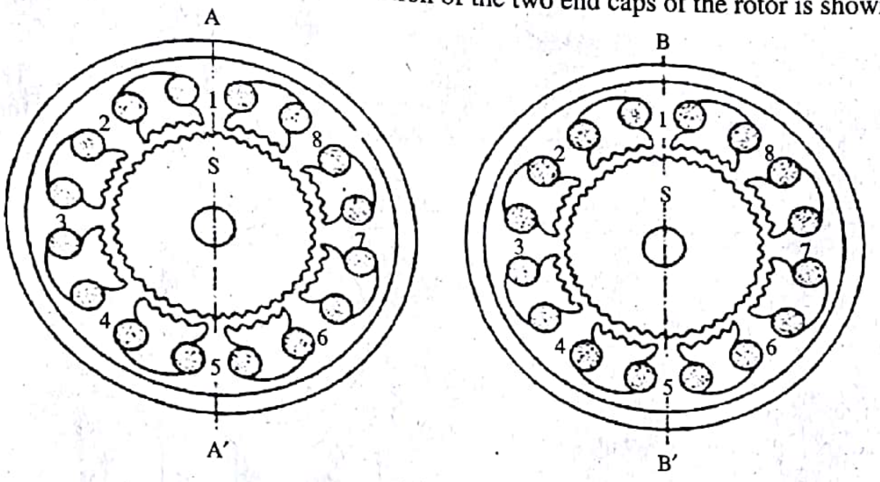


Figure 2.6

The stator has 8 poles, each of which has one coil and S number of teeth. There are 40 poles on the stator, and each end cap has 50 teeth. As the stator and rotor teeth are 40 and 50 respectively, the step angle is expressed as shown below:

$$\text{Step Angle} = \frac{(50-40)\times 360°}{50\times 40} = 1.8°$$

The rotor teeth perfectly aligned with the stator teeth. The teeth of the two end caps are displaced from each other by half of the pole pitch. As the magnet is axially magnetised, all the teeth on the left and right end cap acquire polarity as south and North Pole respectively.

The coils on poles 1, 3, 5 and 7 are connected in series to form phase A. Similarly, the coils on the poles 2, 4, 6 are 8 are connected in series to form phase B.

When phase is excited by supplying a positive current, the stator poles 1 and 5 becomes South poles and stator pole 3 and 7 becomes North poles. Now, when the phase A is de-energised, and phase B is excited, the rotor will turn by a full step angle of 1.8° in the anticlockwise direction. The phase A is now energised negatively; the rotor moves further by 1.8° in the same anticlockwise direction. Further rotation of the rotor requires phase B to be excited negatively.

Thus, to produce anticlockwise motion of the rotor the phases are energised in the following sequence $^{+}$A, $^{+}$B, $^{-}$B, $^{+}$B, $^{+}$A .... For the clockwise rotation, the sequence is $^{+}$A, $^{-}$B, $^{+}$B, $^{+}$A........

One of the main advantages of the Hybrid stepper motor is that, if the excitation of the motor is removed, the rotor continues to remain locked in the same position as before the removal of the excitation. This is because of the Detent Torque produced by the permanent magnet.

Ques 7) Write Comparison between variable reluctance, permanent magnet, and hybrid type stepper motor on the basis of advantages and disadvantages.

Ans: Comparison between Variable reluctance, Permanent Magnet and Hybrid Type Stepper Motor

Table 2.1: Comparison Based on Motor Advantages and Disadvantages

Motor Type	Advantages	Disadvantages
Variable Reluctance Motor	1) Robust – No magnet 2) Smooth movement due to no cogging torque. 3) High steeping rate and speed slewing capability.	1) Vibrations. 2) Complex circuit for control. 3) No smaller step angle. 4) No detent torque.
Permanent Magnet Stepper Motor	1) Detent torque. 2) Higher holding torque. 3) Better damping	1) Bigger step angle. 2) Fixed rated torque. 3) Limited power output and size.
Hybrid Stepper Motor	1) Detent torque. 2) No cumulative position error. 3) Smaller step angle. 4) Operate in open loop	1) Resonance 2) Vibration

Ques 8) Write a short note with proper diagram on:
i) Bifilar windings
ii) Monofilar windings

Ans Bifilar Windings

Bifilar wound motors means that there are two identical sets of windings on each stator pole. This type of winding configuration simplifies operation in that transferring current from one coil to another one, wound in the opposite direction, will reverse the rotation of the motor shaft.

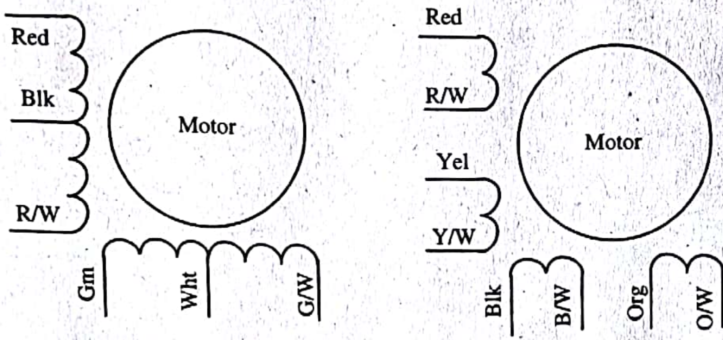


Figure 2.7: 6 and 8 Lead Bifilor Wind Motors

The most common wiring configuration for bifilar wound stepping motors is 8 leads because they offer the flexibility of either a series or parallel connection. There are however, many 6 lead stepping motors available for series connection application

Monofilar Winding

For stepping motors, there are monofilar winding and bifilar windings. For VR type stepping motors, monofilar winding is usually adopted but for PM type and HB types both kinds of winding are used. As shown in **figure 2.8,** in monofilar winding 1 group of salient poles have 1 group of windings to form 1 phase.

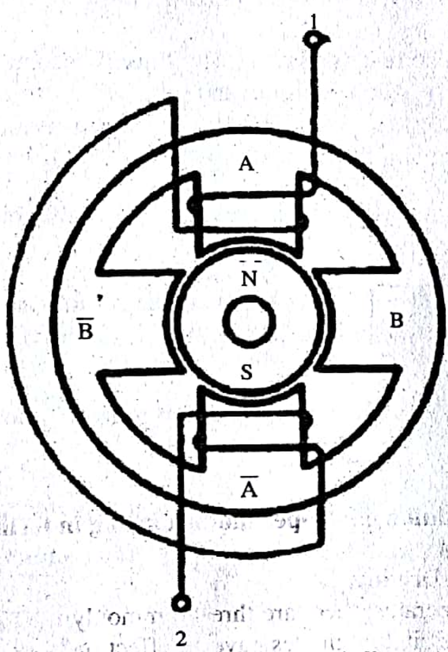


Figure 2.8 Monofilar Winding

In this winding system, there are two kinds of driving systems, one is unipolar drive (**Figure 2.9**) where one excitation state is created by passing current in one direction only and the other is the bipolar drive (**Figure 2.10**) where current is passed in 2 directions to create 2 excitation states. The unipolar drive is mostly used in VR types whereas bipolar drives are used for both PM and HB types.

Monofilar winding for bipolar drive, 4 switching elements corresponding to 1 winding, By comparison, the bifilar winding has 2 phases in which 1 group of salient poles has 2 groups of winding (however, there are grounds for considering it as 1-phase instead of 2-phase).

For PM type and HB types, from the point of the excitation state of stator, the effect is same with monofilar winding and bifilar winding but when monofilar winding is used for bipolar drive, the winding utilisation efficiency and the output are high. The other advantage for this system is that due to the absence of other winding in the identical excitation circuit, the delay of current rise-up owing to mutual inductance can be avoided but the disadvantage is that it makes the driving circuit complicated.

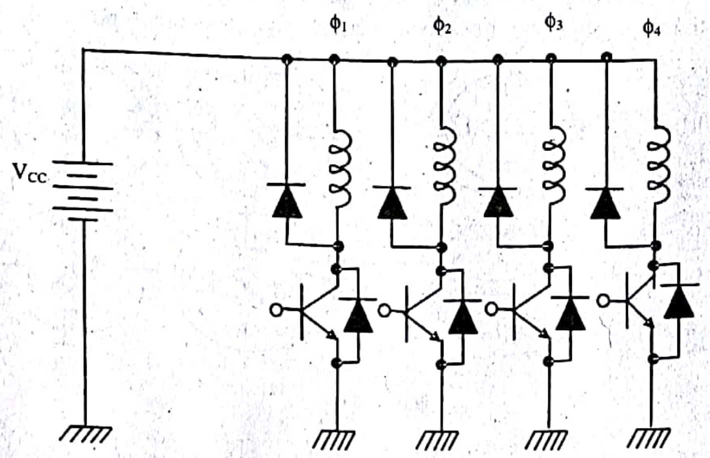


Figure 2.9: Unipolar Driving Circuit

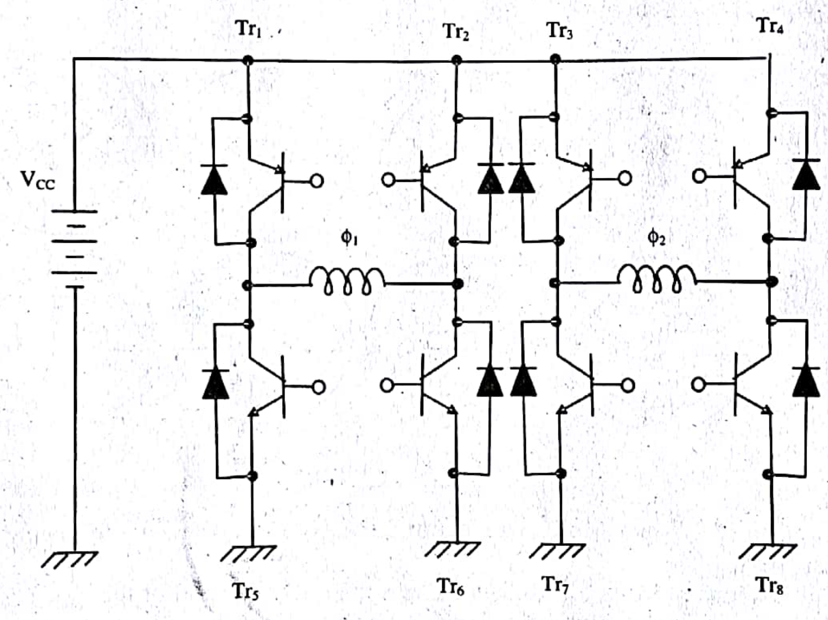


Figure 2.10: Bipolar Driving Circuit

Ques 9) Explain the various modes of excitation of stepper motor driving in terms

Ans: Modes of Excitation of Stepper Motor Driving

Stepper drives control how a stepper motor operates; there are three commonly used excitation modes for stepper motors, full step, half step and microstepping. These excitation modes have an effect on both the running properties and torque the motor delivers.

A stepper motor converts electronic signals into mechanical movement each time an incoming pulse is applied to the motor. Each pulse moves the shaft in fixed increments. If the stepper motor has a 1.8° step resolution, then in order for shaft to rotate one complete revolution, in full step operation, the stepper motor would need to receive 200 pulses, 360° ÷ 1.8 = 200.

There are two types of mode of excitation of stepper motor deriving is explained as follows:

1) **Modes of Excitation of Stepper Motor Driving in Terms of Phase:** There are two types of modes of excitation of stepper motor driving in terms of phase:

i) **Full Step Excitation Mode:** There are two types of full step excitation modes:

a) **In One-Phase on - Full Step:** From **figure**, the motor is operated with only one phase energized at a time. This mode requires the least amount of power from the driver of any of the excitation modes.

b) **In Two-Phase On - Full step:** From **figure**, the motor is operated with both phases energized at the same time. This mode provides improved torque and speed performance. Two-phase on provides about 30% to 40% more torque than one phase on, however it requires twice as much power from the driver.

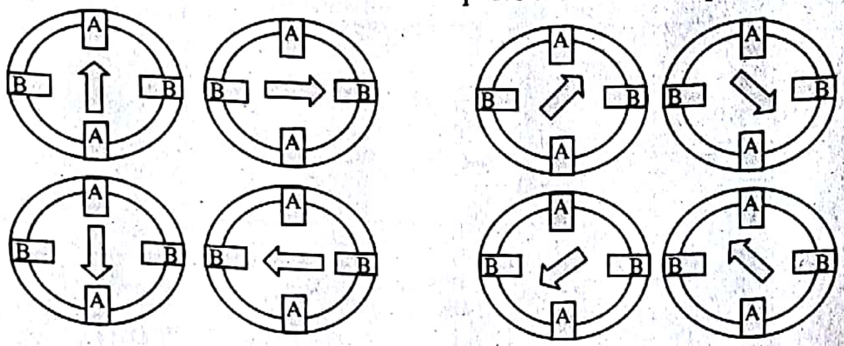


Figure 2.11

ii) **Half Step Excitation Mode:** Half step excitation mode is a combination of one phase on and two phase on full step modes. This results in half the basic step angle. This smaller step angle provides smoother operation due the increased resolution of the angle. Half step produces about 15% less torque than two phase on - full step, however modified half stepping eliminates the torque decrease by increasing the current applied to the motor when a single phase is energized.

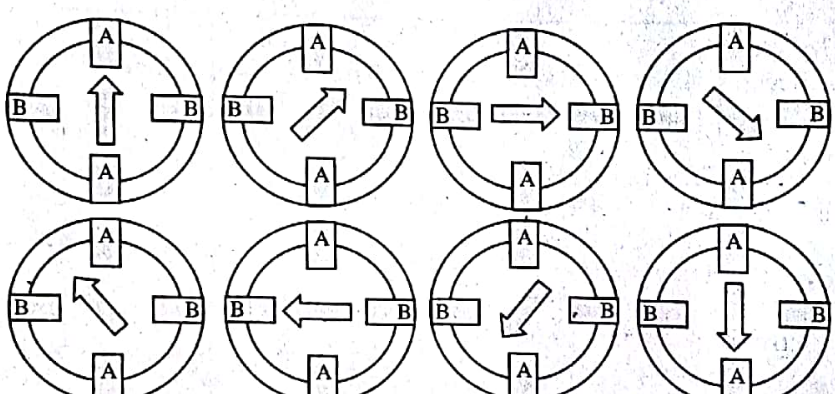


Figure 2.12

2) **Modes of excitation of Stepper Motor Driving in Terms of Coil:** There are following stepper driving modes which are explained as follows:

i) **Single Coil Excitation Mode:** In this mode, at a time only one coil of the motor is energized. All four coils are energized one by one in sequence (please refer the table). In this mode, motor consumes very less power but also provides very less torque. This mode is also known as wave drive and it is not used to drive any load because of very less torque. Usually, stepper motors are not driven in this mode.

Sequence	Motor Coils			
	C1	C2	C3	C4
Step 1	0	0	0	1
Step 2	0	0	1	0
Step 3	0	1	0	0
Step 4	1	0	0	0

ii) **Double Coil Excitation Mode:** In this mode, two motor coils are energized to gather. Then after coils are two coils are energized in sequence (please refer the table). In this mode, motor consumes double the power than single coil excitation mode and provides very high torque. Stepper motors are mostly driven in this mode to drive the load

Sequence	Motor Coils			
	C1	C2	C3	C4
Step 1	0	0	1	1
Step 2	0	1	1	0
Step 3	1	1	0	0
Step 4	1	0	0	1

iii) **Half Step Excitation Mode:** This mode is a combination of above two modes. Please refer the following table to see coil energizing sequence.

Sequence	Motor Coils			
	C1	C2	C3	C4
Step 1	0	0	0	1
Step 2	0	0	1	1
Step 3	0	0	1	0
Step 4	0	1	1	0
Step 5	0	1	0	0
Step 6	1	1	0	0
Step 7	1	0	0	0
Step 8	1	0	0	1

It takes double steps to complete the sequence. When the motor is rotated in this mode, it rotates very smoothly because the step angle of the motor decreases to half (e.g. if motor step angle is 1.8o then in this mode it rotates 0.9o in each step). The step resolution gets doubled. The motor angle can be controlled more precisely and accurately. In this mode, motor consumes moderate power and provides higher torque than single coil excitation mode.

The given project demonstrates how to drive any unipolar stepper motor in these three different modes. It uses arduino UNO board and unipolar stepper motor library to drive the stepper motor. It also controls speed (RPM) of the motor and displays the current speed and driving mode on LCD. So let us first see the circuit diagram followed by its description and working.

Ques 10) Explain the drive circuits of stepper motor. Also give the comparison between them.

Ans: Drive Circuits of Stepper Motor

The main function of the driver circuit is to change the current and flux direction in the phase windings. Driving a controllable amount of current through the windings and thereby enabling maintains of short current rise and fall time is good for high speed performance. The direction change is done by changing the current direction, and this may be done in two different ways using a unipolar or a bipolar drive which is explained as follows:

1) **Unipolar Driver:** Winding has three leads each at the end and one in the middle. Half of the winding only is used in motor operation at any instant of time. To change 25 the direction of rotation, end leads are chosen and the current flows in the same direction. Unipolar winding driver circuit is simple and shown in **figure 2.13.**

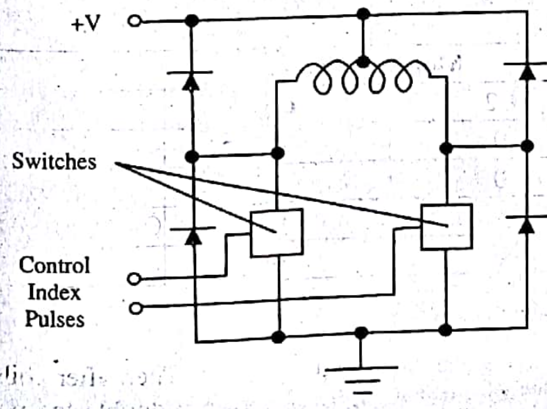


Figure 2.13

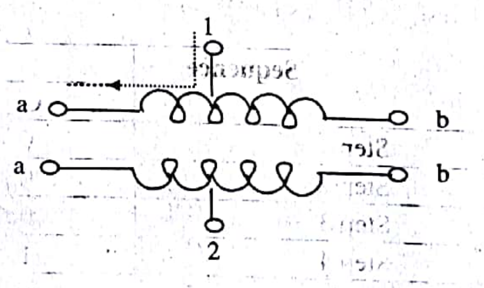


Figure 2.14: Unipolar Winding

2) **Bipolar Driver:** In bipolar winding current flows in both directions as shown in Figure 2.15. Unipolar winding can be configured into bipolar if the centre lead is ignored. Bipolar drives are most widely used drives for industrial applications. Winding is changed by shifting the voltage polarity across the winding terminal. To change polarity, a total of four switches are needed forming an H-bridge. The bipolar drive method requires one winding per phase. The motor winding is fully energized by turning on one set (top and bottom) of the switching transistors. Comparison between different drivers is tabulated in **table 2.2.**

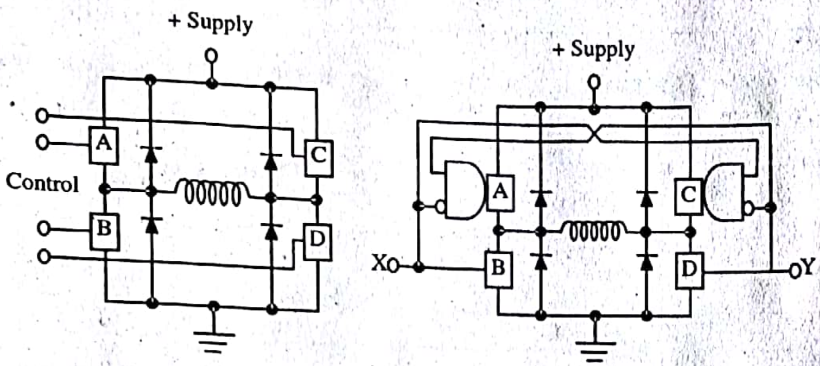


Figure 2.15

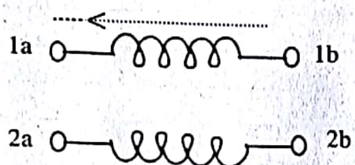


Figure 2.16: Bipolar Winding

Comparison between Unipolar and Bipolar Driver

The Comparison between Unipolar and Bipolar Driver are shown in table **table 2.2:**

Table 2.2: Comparison between Unipolar Driver and Bipolar Driver

Unipolar Driver	Bipolar Driver
Winding with a centre tap, or two sperate windings per pahse.	One winding per phase
Two switcehs per phase	Four switches per phase, in the form of an H-bridge.
Utilises only half the avialble copper volume of winding	Motor winding is fully energised.
Incurs twice the loss if a bipolar drive at the same output power.	Loss is minimum compared to unipolar drive.

Ques 11) Explain static and dynamic characteristics of stepper motor with suitable diagram and discuss an example.

Ans: Static Characteristics

These characteristics include:

1) **Torque Displacement Characteristics:** This gives relationships between electromagnetic torque developed and displacement angle from steady state position. These characteristics are shown in the **figure 2.17.**

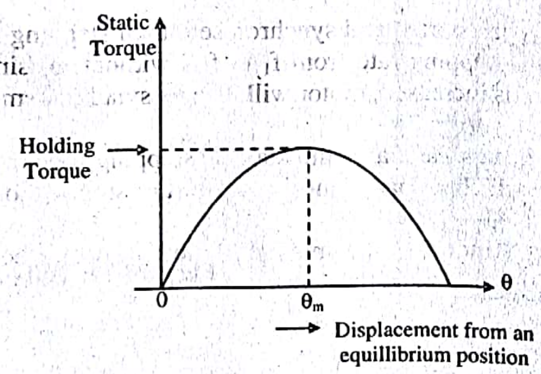


Figure 2.17: Torque Displacement Characteristics

2) **Torque Current Characteristics:** The holding torque of the stepper motor increases with the exciting current. The relationship between the holding torque and the current is called as torque-current characteristics. These characteristics are shown in the **figure 2.18**.

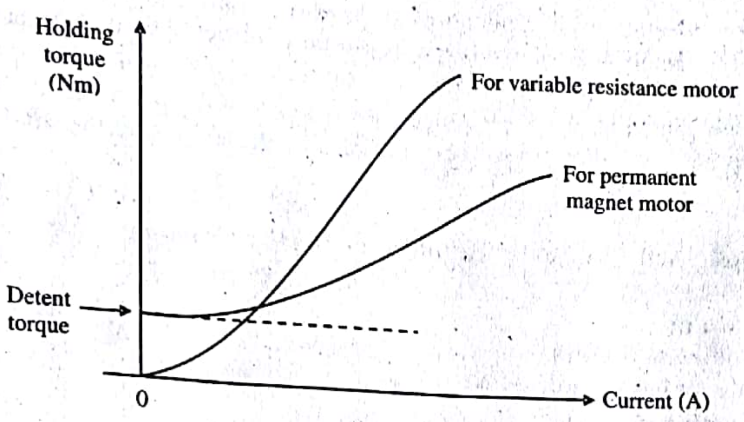


Figure 2.18: Torque Current Characteristics

Dynamic Characteristics

The stepping rate selection is very important in proper controlling of the stepper motor. The dynamic characteristics give the information regarding torque stepping rate. These are also called torque stepping rate curves of the stepper motor. These curves are shown in the **figure 2.19**.

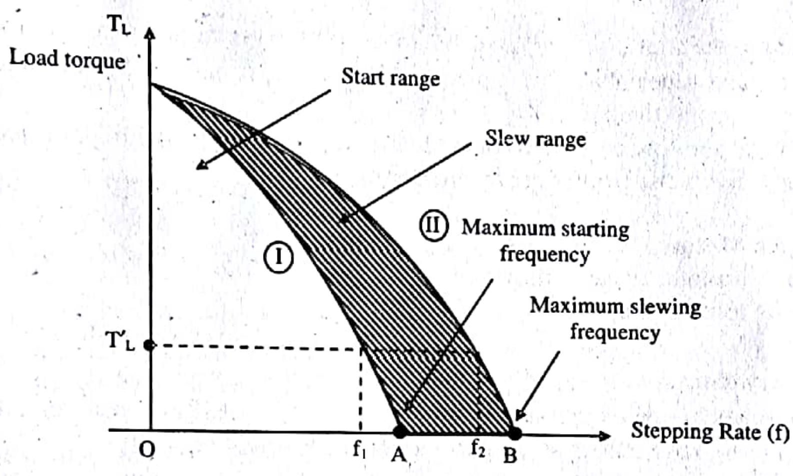


Figure 2.19: Torque Stepping Rate Characteristics

When stepping rate increases, rotor gets less time to drive the load from one position to other. If stepping rate is increased beyond certain limit, rotor cannot follow the command and starts missing the pulses.

Now if the values of load torque and stepping rate are such that point of operation lies to the left of curve I, then motor can start and synchronise without missing a pulse.

For example, for a load torque of T'_L, the stepping rate selection should be less than f_1 so that motor can start and synchronise, without missing a step.

But the interesting thing is that once motor has started and synchronised, then stepping rate can be increased, e.g., upto f_2 for the above example. Such as increase in stepping rate from f_1 to f_2 s without missing a step and without missing the synchronism. But beyond f_2, if stepping rate is increased, motor will lose its synchronism.

So point A as shown in the **figure 2.19** indicates the maximum starting stepping rate or maximum starting frequency. It is defined as the maximum stepping rate with which unloaded motor can start or stop without losing a single step.

While point B as shown in the **figure 2.19** indicates the maximum slewing frequency. It is defined as the maximum stepping rate which unloaded motor continues to run without missing a step.

Thus area between the curves I and II shown hatched indicates, for various torque values, the range of stepping rate which the motor can follow without missing a step, provided that the motor is started and synchronised. This area of operation of the stepper motor is called slew range. The motor is said to be operating in slewing mode.

It is important that in a slew range the stepper motor cannot be started, stopped or reversed without losing steps.

Thus slew range is important for speed control application. In position control, to get the exact position the motor may be required to be stopped or reversed. Hence slew range is not useful for position control applications.

To achieve the operation of the motor in the slew range motor must be accelerated carefully using lower pulse rate. Similarly to stop or reverse the motor without losing acceleration and deceleration of the stepper motor, without losing any step is called ramping.

Ques 12) Write the advantages, disadvantages and application of stepper motor

Ans: Advantages of Stepper Motor

The advantages of stepper motor are as follows:

1) At standstill position, the motor has full torque. No matter if there is no moment or changing position.
2) It has a good response to starting, stopping and reversing position.
3) As there is no contact brushes in the stepper motor, It is reliable and the life expectancy depends on the bearings of the motor.
4) The motor rotation angle is directly proportional to the input signals.
5) It is simple and less costly to control as motor provides open loop control when responding to the digital input signals.
6) The motor speed is directly proportional to the input pulses frequency, this way a wide range of rotational speed can be achieved.
7) When load is coupled to the shaft, it is still possible to realize the synchronous rotation with low speed.
8) The exact positioning and repeatability of movement is good as it has a 3-5% accuracy of a step where the error is non-cumulative from one step to another.
9) Stepper motors are safer and low cost (as compared to servo motors), having high torque at low speeds, high reliability with simple construction which operates at any environment.

Disadvantages of Stepper Motors

The disadvantages of stepper motor are as follows:

1) Stepper motors having low Efficiency.
2) It has low Accuracy.
3) Its torque declines very quickly with speed.
4) As stepper motor operates in open loop control, there is no feedback to indicate potential missed steps.
5) It has low torque to inertia ratio means it can't accelerate the load very quickly.
6) They are noisy.

Applications of Stepper Motor

The applications of stepper motor are as follows:

1) As the stepper motor are digitally controlled using an input pulse, they are suitable for use with computer controlled systems.
2) They are used in numeric control of machine tools.
3) Used in tape drives, floppy disc drives, printers and electric watches.
4) The stepper motor also use in X-Y plotter and robotics.
5) It has wide application in textile industries and integrated circuit fabrications.
6) The other applications of the Stepper Motor are in spacecraft launched for scientific explorations of the planets etc.
7) These motors also find a variety of commercial, medical and military applications and also used in the production of science fiction movies.
8) Stepper motors of microwatts are used in the wrist watches.
9) In the machine tool, the stepper motors with ratings of several tens of kilowatts is used.

Module 3

Single Phase Special Electrical Machines

SINGLE PHASE SPECIAL ELECTRICAL MACHINES

Ques 1) What is a single phase special electrical machine? Give the classification of single phase special electrical machine.

Ans: Single-Phase Special Electrical Machine

Single-phase supply is mainly used for lighting purposes in offices, shops, schools, houses. Besides lighting purposes, it has tremendous uses in our day-to-day life. Domestic applications include mixers, automatic washing machines, electric iron, hair dryers and others. The power rating of these types of machines is very small. These motors are also called fractional kilowatt motors because some of them have rating less than a kilowatt.

Single phase induction motors have very wide applications in household appliances. They are mostly used in small sizes in fraction horsepower range. However, they can be used in industries up to 2 horsepower range. In 1/8 to 3/4 horsepower range these motors are widely used for fans, washing machines, refrigerators, blowers, centrifugal pumps, etc.

The sizes ranging from 1/300 to 1/20 horsepower are used in toys, hairdryers, vending machines, etc. Single phase induction motors run at relatively low power factor and have relatively poor efficiency. The main difficulty of single phase induction motors is that they have no starting torque and hence need some auxiliary means to start them.

Classification of Single Phase Special Electrical Machine

The various types of single phase special electrical machines are discussed as follows:

1) **Single Phase Induction Motor:** The single phase induction motor are simple in construction, cheap in cost, reliable and easy to repair and maintain. Due to all these advantages, the single phase motor finds its application in vacuum cleaners, fans, washing machines, centrifugal pumps, blowers, washing machines, etc.
   i) **Resistance Split Type:**It has a single cage rotor, and its stator has two windings known as main winding and starting winding. Both the windings are displaced 90 degrees in space.
   ii) **Capacitor Split type:**Single phase Induction Motor that employs a capacitor in the auxiliary winding circuit to produce a greater phase difference between the current in the main and the auxiliary windings.
   iii) **Shaded Pole Type:**The shaded pole induction motor is simply a self-starting single-phase induction motor whose one of the pole is shaded by the copper ring.
2) **Single Phase Synchronous Motor:** Single phase synchronous motors are available in small sizes for applications requiring precise timing such as time keeping, (clocks) and tape players. Though battery powered quartz regulated clocks are widely available, the AC line operated variety has better long term accuracy—over a period of months.
   i) **Reluctance Motor:** If the rotating field of a large synchronous motor with salient poles is de-energized, it will still develop 10 or 15% of synchronous torque. There is no practical application for a large synchronous reluctance motor.
   ii) **Hysteresis Motor:** Hysteresis motor is defined as a synchronous motor that is having cylindrical rotor and works on hysteresis losses induced in the rotor of hardened steel with high retentivity. It is a single phase motor and its rotor is made of ferromagnetic material with non magnetic support over the shaft.
3) **Single Phase Induction Motor:** There is another types of single phase induction motor which is explained as follows:
   i) **AC Series Motor:** AC series motor or the universal motor is an electric motor which operates in either Ac or Dc power at the same speed and output.
   ii) **Universal Motor:** A universal motor is a series wound electric motor that can operate on both AC and DC power. These are a lot comparative to those of DC series motors but the series motor develops less torque when working from an AC supply than when working from an equivalent DC supply.

4) **Special Purpose Motor:** There are two types of special purpose motor which are explain as follows:
   i) **Stepper Motor:** A stepper motor is an electromechanical device it converts electrical power into mechanical power. Also it is a brushless, synchronous electric motor that can divide a full rotation into an expansive number of steps.

   ii) **Servomotors:** A servo motor is one of the widely used variable speed drives in industrial production and process automation and building technology worldwide.

Ques 2) Explain principle of operation of Single Phase Special Electrical Machine and also sketch the torque - slip characteristics of single phase special electrical machine.

Ans: Principle of Operation of Single Phase Special Electrical Machine
The stator winding of single phase induction motor is similar to three phase induction motor but the rotor is always squirrel cage. The operation of a three phase induction motor depends on the rotating field produced by the three phase stator currents. The single phase stator winding of a single phase induction motor produces only an alternating field and is not capable of producing a rotating field. So, a single phase induction motor does not start itself as it has no starting torque. However, its running characteristic is satisfactory.

A single phase induction motor must, therefore, have some auxiliary means to start the motor. The single phase induction motor may be regarded as a three phase induction motor with one line disconnected. So, unbalanced currents are drawn from the three phase supply. The unbalanced currents may be represented by equal positive and negative sequence currents. These two sets of three phase currents produce two rotating fields of equal and constant magnitudes, but rotating in opposite directions. The magnitude is equal to half the maximum value of the resultant alternating field.

The flux rotating in the direction of the rotor rotation is called the forward field, while the other is called the backward field. If N is the rotor speed and N_s is the synchronous speed, the slip for forward field directions. The magnitude is equal to half the maximum value of the resultant alternating field. The flux rotating in the direction of the rotor rotation is called the forward field, while the other is called the **backward field.** If N is the rotor speed and N_s is the synchronous speed, the slip for forward field,

$$s_F = (N_s - N)/N_s$$

and the slip for backward field,

$$s_B = (N_s + N)/N_s = [2N_s - (N_s - N)]/N_s$$
$$= (2 - s_F)$$

In case of a three phase induction motor, the torque-slip characteristics are known. Similarly for each rotating field, there is an identical torque-slip characteristic for single phase induction motor. The two torque-slip characteristics and their resultant are shown in **figure 3.1**.

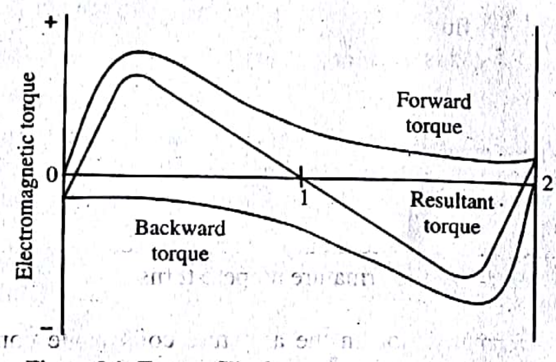


Figure 3.1: Torque-Slip Characteristics of Single Phase Induction Motors

From the above characteristics of single phase induction motors, the following conclusions can be drawn:
1) At unity slip (i.e., at the time of starting), the resultant torque is zero. The motor is, therefore, not self-starting. This means that there is no resultant torque at the time of starting, whatever be the rotor resistance.
2) If it is rotated in any direction, it gets a resultant torque which increases with the speed and hence, the motor rotates in the direction in which it has been initially rotated. Thus the direction of rotation of the motor depends merely upon the direction in which it is started

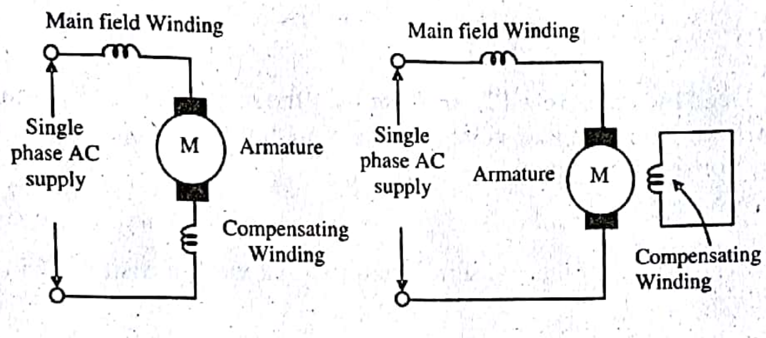
Ques 3) Explain construction and principle of working of AC series motor.

Ans: AC Series Motor

When apply an alternating E.M.F to the terminals, alternating current flows through both the field and the armature windings; so the field winding produces an alternating flux (this produced flux is only alternating not rotating) this flux reacts with the armature current to produce torque.

Construction

In a normal DC motor if direction of both field and armature current is reversed, the direction of torque remains unchanged. So when normal DC series motor is connected to an AC supply, both field and armature current get reversed and unidirectional torque gets produced in the motor hence motor can work on AC supply.



(a) Conductively compensated motor **(b) Inductively compensated motor**

Figure 3.2

But performance of such motor is not satisfactory due to the following reasons:

1) There are tremendous eddy current losses in the yoke and field cores, which causes overheating.
2) Armature and field winding offer high reactance to a.c. due to which operating power factor is very low.
3) The sparking at brushes is a major problem because of high voltage and current induced in the short circuited armature coils during the commutation period.

Principle of Working

Modifications are required to have the satisfactory performance of DC series motor on AC. supply, when it is called AC series motor. The modifications are:

1) To reduce the eddy current losses, yoke and pole core construction is laminated.
2) The power factor can be improved by reducing the magnitudes of field and armature reactance. Field reactance can be decreased by reducing the number of turns. But this reduces the field flux. But this reduction in flux ($N \alpha 1/\Phi$), increases the speed and reduce the torque. To keep the torque same it is necessary to increase the armature turns proportionately. This increases the armature inductance.

Now to compensate for increased armature flux which produce severe armature reaction, it is necessary to use compensating winding. The flux produced by this winding is opposite to that produced by armature and effectively neutralizes the armature reaction.

If such a compensating winding is connected in series with the armature as shown in the **figure 3.2(a),** the motor is said to be 'conductively compensated'. For motors to be operated on AC and DC both, the compensation should be conductive. If compensating winding is short circuited on its self as shown in the **figure 3.2(b)**, the motor is said to be 'inductively compensated'. In this compensating winding acts as a secondary of transformer and armature as its primary. The ampere turns produced by compensating winding neutralize the armature ampere turns.

To reduce the induced e.m.f. due to transformer action in the armature coils while commutation period, the following measures are taken:

1) The flux per pole is reduced and number of poles is increased.
2) The frequency of supply used is reduced.
3) Preferrably single turn armature coils are used.

Ques 4) Explain phasor diagram of AC series motor.

Ans: Phasor Diagram of AC Series Motor

Given in **figure 3.3** is the phasor diagram for the AC series motor. The phasor diagram for an AC series motor, Before we draw phasor diagram, let us write the various notations for each quantity at one place. Here we will use:

Rs to represent the resistance of the series field
Rp to represent the resistance of the inter pole circuit
Rc to represent the resistance of the compensation winding
Ra to represent the resistance of the armature circuit
Xs to represent the reactance of the series field
Xp to represent the reactance of the inter pole circuit
Xc to represent the reactance of the compensation winding
Xa to represent the reactance of the armature circuit
I to represent the current in the circuit

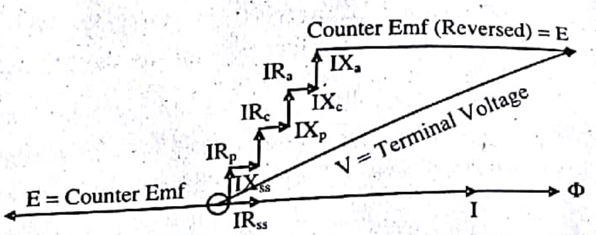


Figure 3.3

ϕ to represent the flux produced by the current I

Now assumed that the flux produced by the current I is in phase with the current I due very small lagging angle. On taking the current on the reference axis we have terminal voltage equals to summation of all the voltage drops and the counter emf. We have summation of the voltage drops equal.

$$\mathbf{I \times [(R_s + R_p + R_c + R_a) + j(X_s + X_p + X_c + X_a}$$

The main **advantage** of the phasor diagram of the AC series motor is that we can easily obtain the phase angle for counter emf E with the help of phasor diagram.

Ques 5) Explain the characteristics of single phase AC series motor. Write the applications of it.

Ans: Characteristics of Single Phase AC Series Motor.

There are following characteristics of AC series motor

1) **Power Factor Characteristics:** The expression for power factor with the help of phasor diagram given above. From the phasor diagram we write sine of angle ϕ as

$$= \frac{\text{Summation of the reactance drop}}{\text{Terminal voltage}}$$

$$\text{Mathematically, } \sin\phi = I \times \frac{X_s + X_p + X_c + X_a}{V} = I\frac{X}{V}I$$

From this, we can write the expression for power factor is equal to; $\left(1 - iI\frac{X}{V}\right)^{0.5}$

Clearly from the above equation we can say that if we want the high value of power factor, the value of reactance and counter emf should low as minimum as possible. From point of view of loading, we have low value of power factor at over loading and it is due to the fact that the high value of current. Thus the high value of power can be achieved only if the load is very light.

2) **Speed Current Characteristics:** In order to the understand speed current characteristic let us derive an expression for speed in terms of counter emf. We have a proportional relationship between the counter emf and speed of the motor. Thus if the value of the counter emf is large then the value of speed will be more. From the phasor diagram we can say that the counter emf is equal to the difference between the terminal voltage and the voltage drops. Hence if current cause's higher voltage drops then the generated back emf will be less therefore the speed of the motor will be less.

Let analyse and compare speed current characteristics for both AC and DC series motor. Let us first consider the case of DC series motor: In case of DC series motor we have high value of counter emf because the value of voltage drop here is small. The voltage drops here is due to resistive drops mainly therefore the value of voltage drop is low.

Now Let us consider the case of AC series motor: In case of AC series motor we have a low value of counter emf because the value of voltage drop here is large.

The voltage drops here is due to resistive drops and reactance drop therefore the value of voltage drop is high. It means the speed current characteristics curve for the DC series are less dropping than the AC series motor. Given **figure 3.4** are the characteristics for both the AC and DC series motor.

3) **Torque Current Characteristics:** After neglecting the small value of phase angle (angle between the flux and the current) and saturation effect we can say that the value of the torque is directly proportion to the value of square of the current. Therefore the variation of torque with the current can plotted as shown in the **figure 3.5**:

4) **Torque Speed Characteristics:** The relation between the torque and speed can derived with the help of torque current and speed current characteristics. The torque speed characteristics are plotted as shown in **figure 3.6**.

5) **Power Output Characteristics:** The mechanical output power developed by the AC series motor can be calculated by the product of the counter emf and current. The value of mechanical power developed is directly proportion to the value of the current, if we neglect the decrement in value of the counter emf. The counter emf slightly decreases with the increase in the value of the current. The Power output characteristics are plotted as shown in **figure 3.7.**

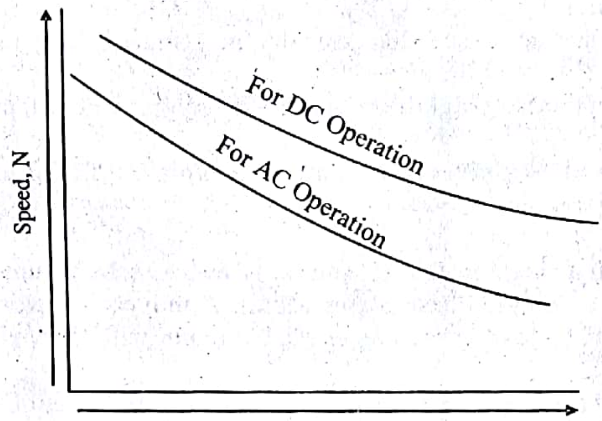


Figure 3.4

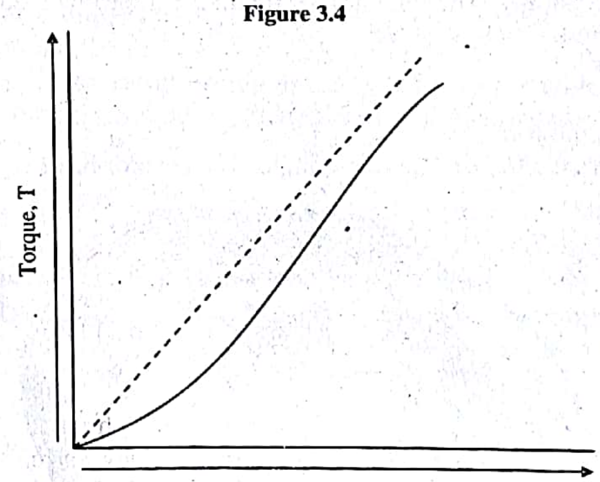


Figure 3.5

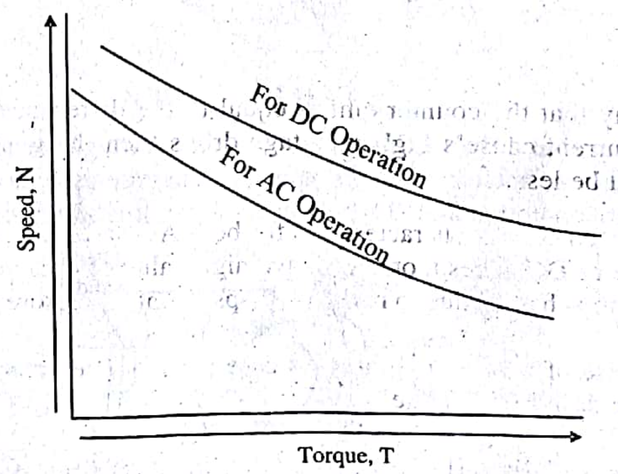


Figure 3.6

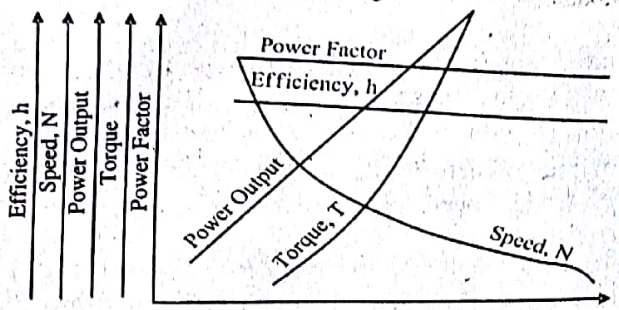


Figure 3.7

Applications of AC series motors:

1) These motors are highly in home appliances like hair dryers, grinders, table fans, polishers and many other kitchen appliances.
2) These motors are also very useful where high speed control is required like lift, cranes, etc.

Ques 6) What do you understand by Universal motor? Also explain types of universal motor.

Ans: Universal Motor

The motors which can be used with a single phase AC source as well as a DC source of supply and voltages are called as Universal Motor. It is also known as Single Phase Series Motor. A universal motor is a commutation type motor. If the polarity of the line terminals of a DC Series Motor is reversed, the motor will continue to run in the same direction.

A universal motor is a series wound electric motor that can operate on both AC and DC power. These are a lot comparative to those of DC series motors but the series motor develops less torque when working from an AC supply than when working from an equivalent DC supply. The direction of rotation can be changed by interchanging connections to the field with respect to the armature as in DC series motor.

Types of Universal Motor

There are two types of universal motor:

1) **Non-Compensated Universal Motor:** The non-compensated motor has two salient poles and it is laminated as shown in **figure 3.8.**

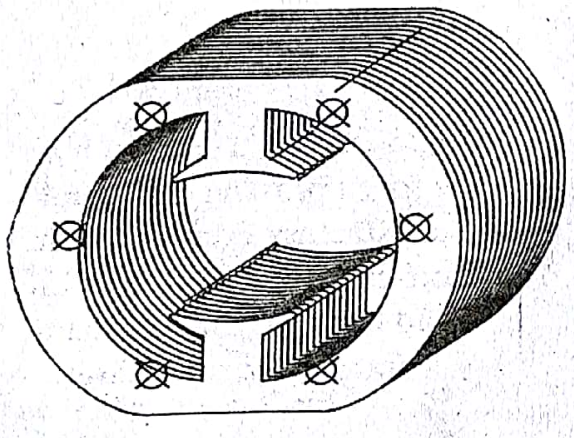


Figure 3.8

The armature is of wound type and the laminated core is either straight or skewed slots. The leads of the armature winding are connected to the commutator. High resistance brushes are used along with this type of motor to help better commutation. An equivalent non-compensated type universal motor is shown in **figure 3.9.**

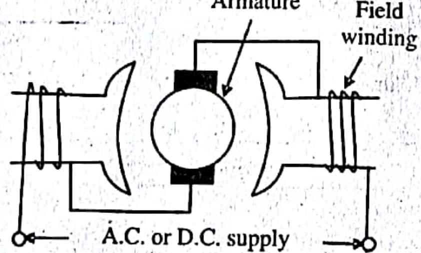


Figure 3.9

2) **Compensated Type with Distributed Field:** The compensated type Universal motor consists of distributed field winding and the stator core is similar to that of split-phase motor. The split phase motors consist of an auxiliary winding in addition to main winding. Similar to the split phase motors, the compensated type also consists of an additional winding. The compensating winding helps in reducing the reactance voltage which is caused due to alternating flux, when the motor runs with the AC supply.

An equivalent compensated type universal motor is shown in **figure 3.10**.

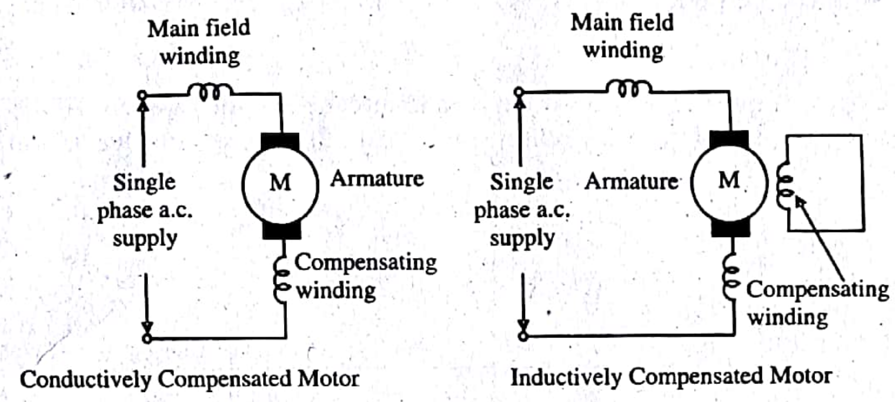


Figure 3.10

Ques 7) Discuss about the construction and working principle of universal motor with suitable diagram. Also sketch the output waveform of universal motor

Ans: Construction of Universal Motor

The construction of a universal motor is very similar to the construction of a DC machine. It consists of a stator on which field poles are mounted. Field coils are wound on the field poles. However, the whole magnetic path (stator field circuit and also armature) is laminated. Lamination is necessary to minimize the eddy currents which induce while operating on AC. The rotary armature is of wound type having straight or skewed slots and commutator with brushes resting on it. The commutation on AC is poorer than that for DC. Because of the current induced in the armature coils. For that reason brushes used are having high resistance.

Working Principle of Universal Motor

The working of a universal motor is similar to a series dc motor. On the other hand, the universal motor is designed for AC operation. It is competent to work at either AC or DC current. In this manner its development is a little distinctive. The field winding and armature winding are connected in series; both windings are energized when voltage is applied to the motor. The field and armature windings produce magnetic field which cause armature to rotate. Modest universal motors usually have no remuneration and replacement winding; they have two salient poles with excitation winding. The response between magnetic fields is caused by either AC or DC power.

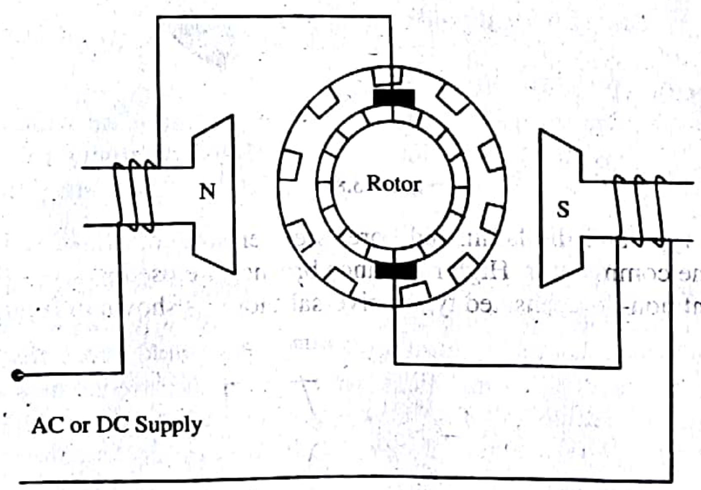


Figure 3.11

When fed with AC supply, it still produces unidirectional torque. Because, armature winding and field winding are connected in series, they are in same phase. Hence, as polarity of AC changes periodically, the direction of current in armature and field winding reverses at the same time.

Thus, direction of magnetic field and the direction of armature current reverses in such a way that the direction of force experienced by armature conductors remains same. Thus, regardless of AC or DC supply, universal motor works on the same principle that DC series motor works.

The direction is determined by both field polarity and the direction of current through the armature. As torque is proportional to the flux and the armature current. Let the DC series motor be connected across a single phase AC supply. Since the same current flows through the field winding and the armature winding. The AC reversal from positive to negative or vice versa will affect the field flux polarity and the current direction through the armature.

Output waveform

The direction of the developed torque will remain positive, and direction of the rotation will be as it was before. The nature of the torque will be pulsating, and the frequency will be twice that of line frequency waveform as shown in **figure 3.12**.

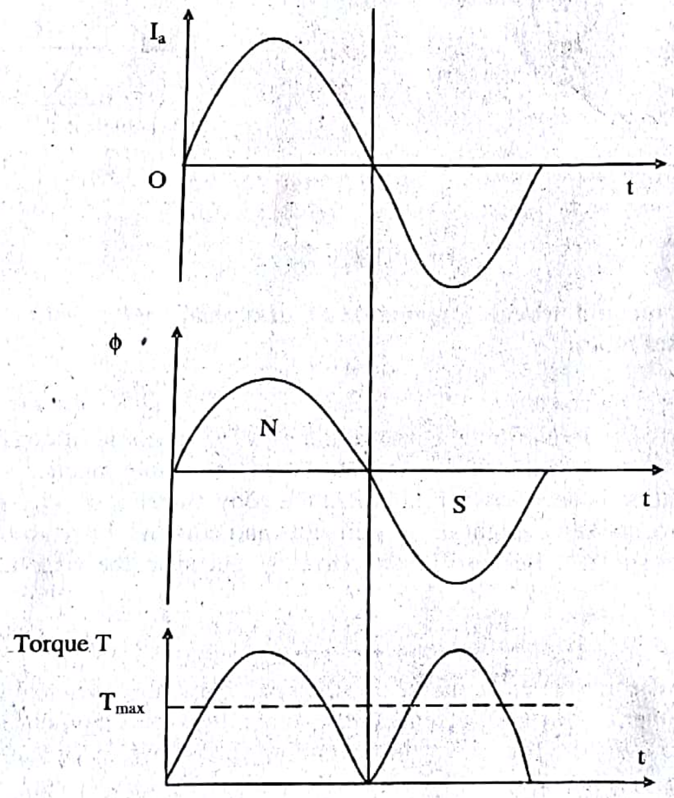


Figure 3.12

Ques 8) How can a universal motor operate on either DC or AC supply?

Ans: Universal Motor Operate on either DC or AC Supply

A universal motor is a series-wound motor meaning that the field and armature windings are connected in series and is mechanically commutated with brushes and a commutator. Although its construction is very similar to a series-wound DC motor, a universal motor incorporates several modifications that allow it operate properly on either DC or AC power supply.

When the motor runs on AC voltage, the alternating flux causes a reactance voltage, which limits the current to a much lower level than would be produced with DC voltage. To limit the effects of this armature reaction, the universal motor uses a compensation winding, which is installed in the slots of the stator, 90 degrees electrical from the main field winding and connected in series with the armature and field winding. (This arrangement is referred to as "conductively compensated.") The current flowing in each coil of the compensating winding is in a direction opposite to the current in the corresponding armature loop near it. The winding of equal coils in opposite directions produces a cancelling effect that reduces inductance, and therefore, reactance.

AC supply also induces more significant eddy currents than are produced when the motor operates on DC supply. To curtail eddy current losses, universal motors use laminated cores (rather than solid iron), which increases their resistance and reduces eddy currents.

A compensating winding is used for reducing the effect of the armature reaction and improving the commutation process. The winding is placed in the stator slots as shown in the **figure 3.13**.

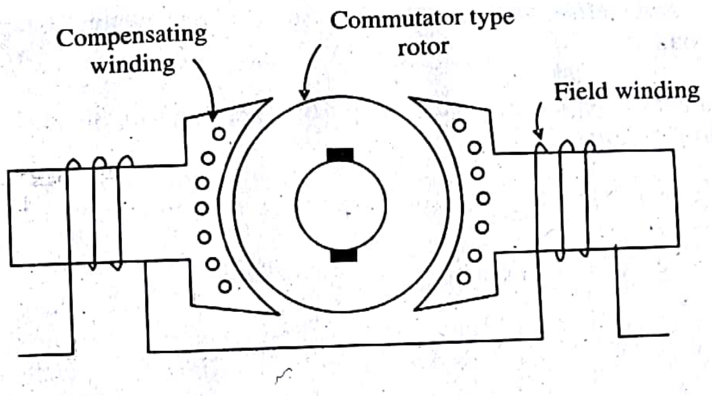


Figure 3.13

The series motor with the compensated winding is shown in the **figure 3.14**.

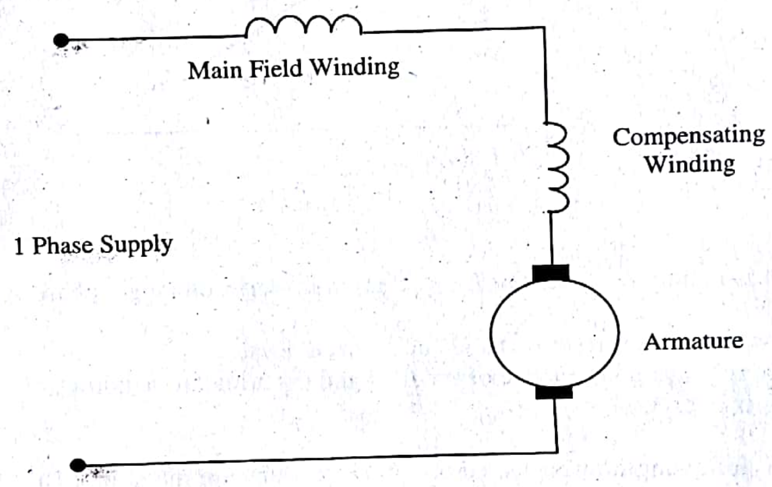


Figure 3.14

The winding is put in the stator slot. The axis of compensating winding is 90 degrees with the main field axis. The compensating winding is connected in series with both the armature and the field, hence, it is called conductively compensated.

If the compensating winding is short circuited, the motor is said to be inductively compensated. The connection diagram is shown in **figure 3.15**.

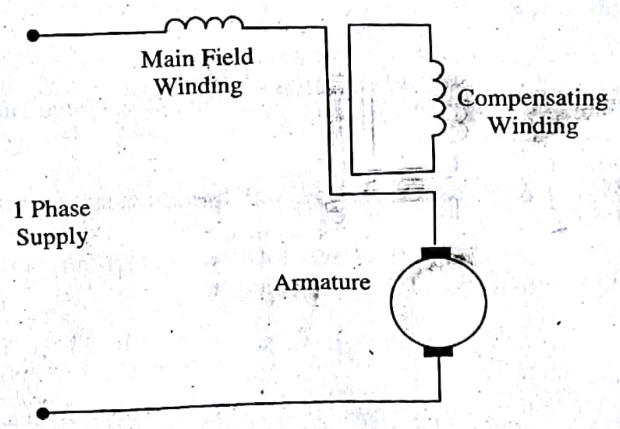


Figure 3.15

Ques 9) Discuss about the speed/ load characteristic of universal motor.

Ans: Speed/Load Characteristics

A speed/load characteristic of a universal motor is similar to that of DC series motor. The speed of a universal motor is low at full load and very high at no load.

Usually, gears trains are used to get the required speed on required load. The speed/load characteristics are (for both AC as well as DC supply) are shown in the **figure 3.16**.

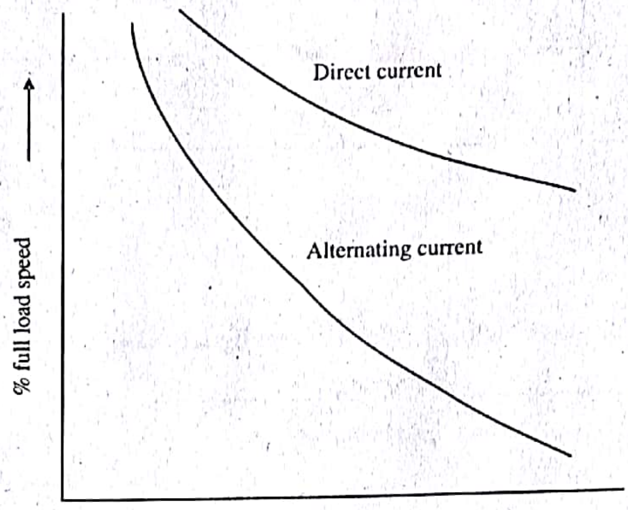


Figure 3.16

However, a series motor which is mainly designed for DC operation if works on single phase AC supply suffers from the following drawbacks.

1) The efficiency becomes low because of hysteresis and eddy current losses.
2) The power factor is low due to the large reactance of the field and the armature windings.
3) The sparking at the brushes is in excess.

In order to overcome the above following drawbacks, certain modifications are made in a DC series motor so that it can work even on the AC current. They are as follows:

1) The field core is made up of the material having a low hysteresis loss. It is laminated to reduce the eddy current loss.
2) The area of the field poles is increased to reduce the flux density. As a result, the iron loss and the reactive voltage drop are reduced.
3) To get the required torque the number of conductors in the armature is increased.

Ques 10) What are the advantages and disadvantages of universal motor? Also write its application.

Ans: Advantages of Universal Motor

1) Can run from AC or DC supplies
2) Is a cheap motor
3) It has good torque at low speeds. This makes it useful in e.g. mains operated hand held power tools.

Disadvantages of Universal Motor

1) Brushes and commutator wear out, create sparking which can cause electromagnetic interference and may be an ignition source of VOCs.
2) Speed control is lousy - it has characteristics of series DC motor. On no load it races to high speed and often has a shaft mounted fan to provide some load and prevent runaway.
3) It is not easy to reverse the motor.

Applications of Universal Motor

1) Universal motors find their use in various home appliances like vacuum cleaners, drink and food mixers, domestic sewing machine etc.
2) The higher rating universal motors are used in portable drills, blenders etc.

HYSTERESIS MOTOR

Ques 11) What is Hysteresis motor? Explain construction of Hysteresis motor with suitable diagram.

Or

Explain working principle of hysteresis motor.

Ans: Hysteresis motor

Hysteresis motor is defined as a synchronous motor that is having cylindrical rotor and works on hysteresis losses induced in the rotor of hardened steel with high retentivity. It is a single phase motor and its rotor is made of ferromagnetic material with non-magnetic support over the shaft.

Construction of Hysteresis Motor

1) **Stator:** Stator of hysteresis motor is designed in a particular manner to produce synchronous revolving field from single phase supply. Stator carries two windings, (a) main winding (b) auxiliary winding. In another type of design of hysteresis motor the stator holds the poles of shaded type.

2) **Rotor:** Rotor of hysteresis motor is made of magnetic material that has high hysteresis loss property. Example of this type of materials is chrome, cobalt steel or alnico or alloy. Hysteresis loss becomes high due to large area of hysteresis loop. Rotor does not carry any winding or teeth. The magnetic cylindrical portion of the rotor is assembled over shaft through arbor of non-magnetic material like brass. Rotor is provided with high resistance to reduce eddy current loss.

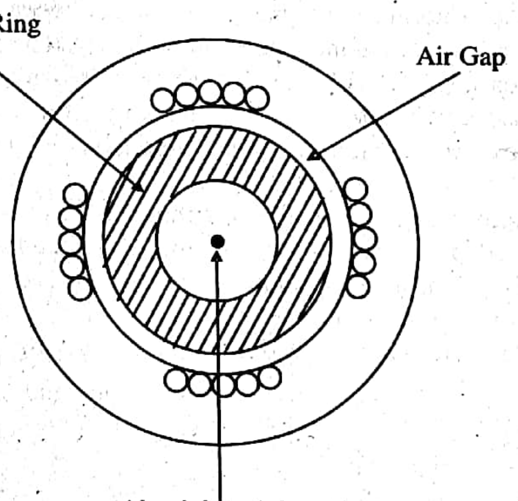
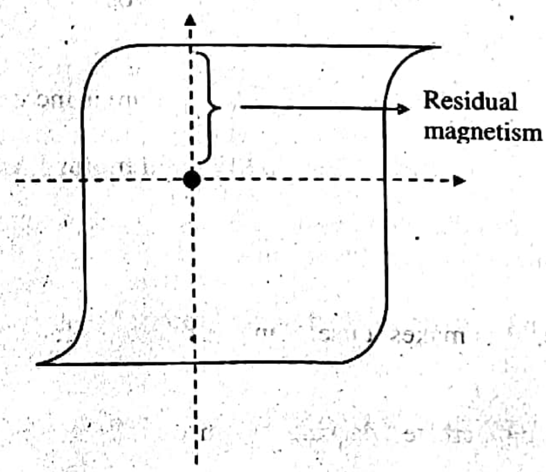


Figure 3.17



Hysteresis loop for rotor material

Figure 3.18

Working Principal of Hysteresis Motor

Starting behaviour of a hysteresis motor is like a single phase induction motor and running behaviour is same as a synchronous motor. Step by step its behaviour can be realized in the working principle that is given below:

1) **At the Starting Condition:** When stator is energized with single phase AC supply, rotating magnetic field is produced in stator.

To maintain the rotating magnetic field the main and auxiliary windings must be supplied continuously at start as well as in running conditions. At the starting, by induction phenomenon, secondary voltage is induced in the rotor by stator rotating magnetic field. Hence eddy current is generated to flow in the rotor and it develops rotor.

Thus eddy current torque is developed along with the hysteresis torque in the rotor. Hysteresis torque in the rotor develops as the rotor magnetic material is with high hysteresis loss property and high retentivity.
The rotor goes under the slip frequency before going to the steady state running condition.So it can be said that when the rotor starts to rotate with the help of these eddy current torque due to induction phenomenon, it behalves like a single phase induction motor.

2) **At Steady State Running Condition:** When the speed of the rotor reaches near about the synchronous speed, the stator pulls the rotor into synchronism. At the condition of synchronism, the relative motion between stator field and rotor field vanishes. So there is no further induction phenomenon to continue. Hence no eddy current to generate in the rotor. Thus the torque due to eddy-currents vanishes.

At the time of rotor's rotation at the synchronous speed, rotating magnetic field flux in the stator produces poles on the rotor by induction; they are named as north (N) and south (S) poles. Thus rotor behaves as a permanent magnet having rotor axis as the induced magnetic axis.For high residual magnetism or retentivity the rotor pole strength remains sustainable or unchanged. Again higher the retentivity, higher is the hysteresis torque and the hysteresis torque is independent of the rotor speed always.

The high retentivity enables the continuous magnetic locking between stator and rotor and thus the motor rotates at synchronous speed. The maximum work done to establish the hysteresis losses under the magnetization cycle in the rotor is equal to the surface area inside B-H hysteresis curve.In lower load torque, the needed work done to rotate the rotor is equal to maximum magnetizing work of hysteresis phenomenon available already in the rotor. So induced magnetic pole axis always follows the rotating magnetic field axis of stator without any lag angle.

But when the load torque is sufficiently high, the maximum magnetizing work in rotor by hysteresis phenomenon cannot fulfil the work done needed to rotate the rotor. So the induced magnetic field axis or rotor pole axis lags the rotating magnetic field axis of the stator at an angle δ_h. Hence the rotor pole axis tries to catch up the stator magnetic field axis.If the load torque is increased, this lagging angle will be increased up to δ_{max} before dropping below the synchronous condition.The rotor poles are attracted towards the moving stator poles and runs at synchronous speed.

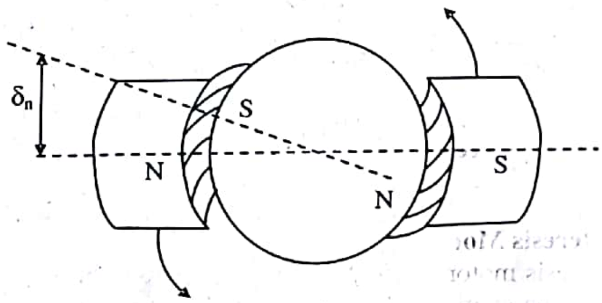


Figure 3.19

As there is no slip at steady state running condition, only hysteresis torque is present to keep the rotor running at synchronous speed and it behaves like a synchronous motor.

Ques 12) What is Hysteresis Power Loss, Ph in Hysteresis Motor? What is the Equation of Hysteresis Torque in the Hysteresis Motor?

Or

Define how hysteresis torque is independent of frequency and speed?

Ans: Hysteresis Power Loss
Hysteresis power loss in the rotor of the hysteresis motor is given by $P_h = K_h f_r B^n_{max}$. Where, f_r is the frequency of flux reversal in the rotor (Hz) B_{max} is the maximum value of flux density in the air gap (T) P_h is the heat-power loss due to hysteresis (W) k_h is the hysteresis constant

$$P_{mech} = P_h\left(\frac{1-s}{s}\right) \quad T_h = \left(\frac{5252 k_h . f . B^n{}_{max}}{n_s}\right)$$

$P_h = k_h.f.B^n{}_{max}$

$\frac{T_h n_r}{5252} = k_h.f.B^n{}_{max}\left(\frac{1-s}{s}\right)$ $n_s = \frac{120.f_s}{P}$

$n_r = n_s(1-s)$ $T_h = \frac{5252 k_h B^n{}_{max}}{\frac{120}{P}}$

$f_r = sf_s$

From the equation of the hysteresis torque, it is clear that hysteresis torque is independent of frequency and speed.

Ques 13) What is a torque slip characteristic of hysteresis motor? Write application of hysteresis motor.

Or

What are speed torque characteristics of Hysteresis motor?

Ans: Torque - Slip characteristics of Hysteresis Motor

Constant Hysteresis Torque occurs in the hysteresis motor. This constant valued torque allows the motor to synchronize any load it can accelerate. The normal operating range is mentioned with dark vertical line.

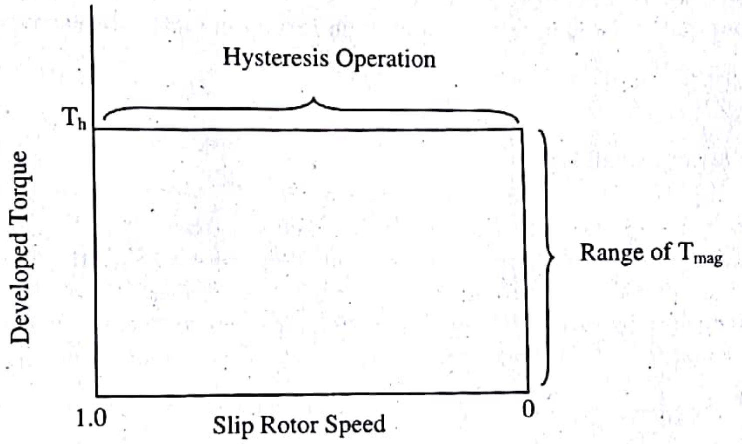


Figure 3.20

Speed-Torque Characteristics of a Hysteresis Motor

The speed-torque characteristic of a hysteresis motor is shown in **figure 3.21**. The torque is almost constant from starting to running condition. At starting condition the starting torque is the eddy current torque along with the hysteresis torque. But in the running condition net running torque means only the hysteresis torque.

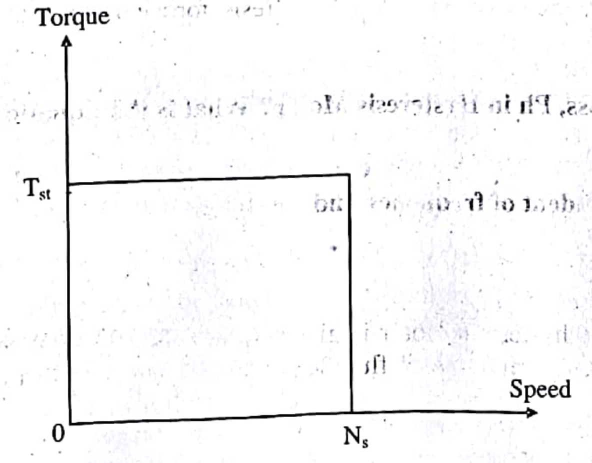


Figure 3.21

Ques 14) Discuss about the all types of hysteresis motor. Write applications of Hysteresis motor.

Ans: Types of Hysteresis Motor

There are various types of hysteresis motor by construction. They are:

1) **Cylindrical Hysteresis Motors:** It has cylindrical rotor.
2) **Disk Hysteresis Motors:** It has annular ring shaped rotor.
3) **Circumferential-Field Hysteresis Motor:** It has rotor supported by a ring of nonmagnetic material with zero magnetic permeability.
4) **Axial-Field Hysteresis Motor:** It has rotor supported by a ring of magnetic material with infinite magnetic permeability.

Advantages

The main advantages of hysteresis motor are given below:

1) As no teeth and no winding in rotor, no mechanical vibrations take place during its operation.
2) Its operation is quiet and noiseless as there is no vibration.
3) It is suitable to accelerate inertia loads.
4) Multi-speed operation can be achieved by employing gear train.

Disadvantages

The disadvantages of hysteresis motor are given below:

1) Hysteresis motor has poor output that is one-quarter of output of an induction motor with same dimension.
2) Low efficiency
3) Low torque.
4) Low power factor
5) This type of motor is available in very small size only.

Application

1) They are widely used in
2) Sound producing equipments,
3) Sound recording instruments,
4) High quality record players,
5) Timing devices
6) Electric clocks,
7) Teleprinters.

Module 4

Reluctance Motor

RELUCTANCE MOTOR

Ques 1) What do you mean by Reluctance Motor? Explain principle of operation of Reluctance motor. Write application of reluctance motor.

Ans: Reluctance Motor

A single phase synchronous Reluctance Motor is basically the same as the single cage type induction motor. The stator of the motor has the main and auxiliary winding. The stator of the single phase reluctance and induction motor are same. The rotor of a reluctance motor is a squirrel cage with some rotor teeth removed in the certain places to provide the desired number of salient rotor poles

Principle of operation

Reluctance motors operate on the principle that forces are established that tend to cause iron poles carrying a magnetic flux to align with each. One form of reluctance motor is shown in cross section in the **figure 4.1.** The rotor consists of four iron poles with no electrical windings. The stator has six poles each with a current-carrying coil. In the condition represented in the figure, current has just been passed through coils a and a′, producing a torque on the rotor aligning two of its poles with those of the a-a′ stator.

The current is now switched off in coils a and a′ and switched on to coils b and b′. This produces a counter clockwise torque on the rotor aligning two rotor poles with stator poles b and b′. This process is then repeated with stator coils c and c′ and then with coils a and a′. The torque is dependent on the magnitude of the coil currents but is independent of its polarity. The direction of rotation can be changed by changing the order in which the coils are energised. Reluctance motors can have other pole configurations, such as eight stator poles and six rotor poles.

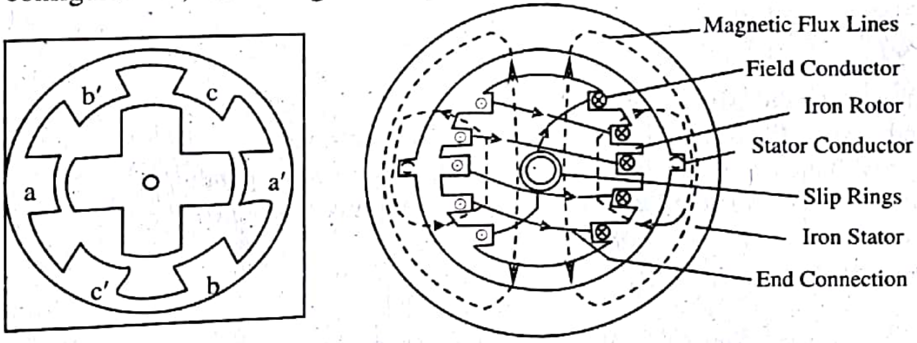


Figure 4.1: Reluctance Motor in Cross Section

The currents in the stator coils are usually controlled by semiconductor switches connecting the coils to a direct voltage source. A signal from a position sensor mounted on the motor shaft is used to activate the switches at the appropriate time instants. Frequently a magnetic sensor based on the Hall effect is employed. (The Hall effect involves the development of a transverse electric field in a semiconductor material when it carries a current and is placed in a magnetic field perpendicular to the current.) The overall system is known as a self-synchronous motor drive. It can operate over a wide and controlled speed range.

In another reluctance motor configuration, the stator is made similar to that of an induction motor and is supplied from a three-phase controllable supply. The rotor consists of longitudinal iron laminations separated by non-magnetic spacers. Flux from the stator encounters much lower reluctance along the laminations than across them.

Reluctance motors can be designed for constant speed operation from a constant frequency supply. The rotor has salient poles without field windings. The stator is cylindrical and contains a three-phase winding similar to that of an induction machine. A damper winding is fitted in the rotor surface so that the machine can start as an induction motor. After the rotor pulls into synchronism with the rotating field of the stator, it operates as a synchronous motor at constant speed.

Applications
1) Simple construction as there is no slip rings, no brushes and no DC field windings.
2) Low cost
3) Maintenance is easy.
4) It is used for many constant speed applications such as electric clock timer, signalling devices, recording instruments, etc.

Ques 2) Define torque equation and torque-slip characteristics of Reluctance motor.

Ans: Torque Equation of Reluctance Motor
Reluctance torque or alignment torque is experienced by a ferromagnetic object placed in an external magnetic field, which causes the object to line up with the external magnetic field. An external magnetic field induces an internal magnetic field in the object and because of this torque is produced.

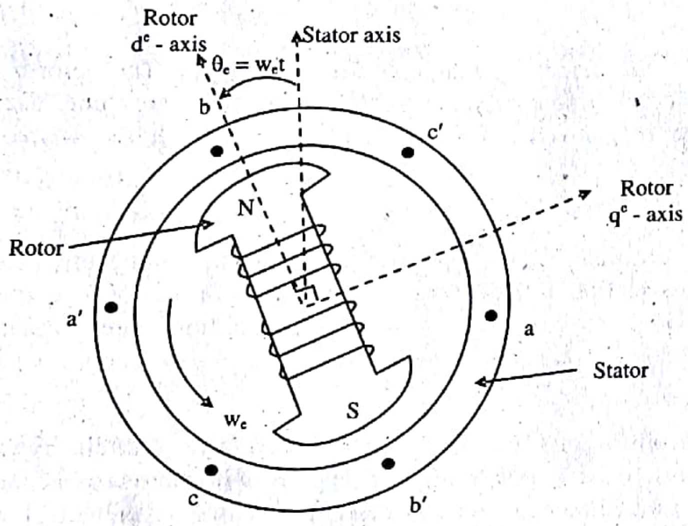


Figure 4.2

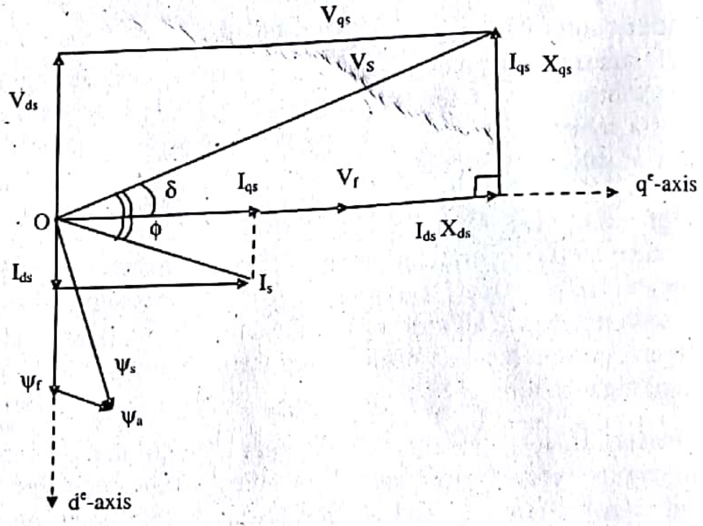


Figure 4.3: Phasor Diagram in Motoring Mode

Let,
V_f = Excitation emf or speed emf with the q^e-axis
ψ_f = Flux linkage induced by the field current (I_f) aligned with the d^e-axis
V_δ , I_δ = Phase supply voltage and phase supply current resolved into corresponding d^e and q^e components
ψ_δ = Stator flux linkage when armature flux linkage ψ_a aids field flux linkage ψ_f
ϕ = Power factor angle between V_s and I_s
δ = Torque angle between V_s and V_f

Consider motoring mode phaser diagram, which is drawn for lagging power factor with $\psi_s > \psi_f$.

Power input to motor, $P_i = 3.V_s\, I_s \cos\phi$ .....(1)

From phaser diagram, $I_s \cos\phi = I_{qs}\cos\delta - I_{ds}\sin\delta$ ....(2)

Substitute Equation (2) in Equation (1),

$P_i = 3.V_s\,(I_{qs}\cos\delta - I_{ds}\sin\delta)$ .....(3)

From phaser diagram, $I_{ds} = \dfrac{V_s\cos\delta - V_f}{X_{ds}}$ .....(4)

And, $I_{qs} = \dfrac{V_s\sin\delta}{X_{qs}}$ .....(5)

Substitute equation (4) and equation (5) in equation (3),

$$P_i = 3V_s\left[\frac{V_s\sin\delta}{X_{qs}}\cos\delta - \frac{V_s\cos\delta - V_f}{X_{ds}}.\sin\delta\right]$$

$$=3V_s\left[\frac{V_s \sin\delta.\cos\delta}{X_{qs}} - \frac{V_s \cdot \sin\ \delta\cos\delta V_f \cdot \sin\delta}{X_{ds}}\right]$$

$$=3V_s\left[\frac{V_s \sin 2\cdot\delta}{2X_{qs}} - \frac{V_s.\sin 2\cdot\delta}{2X_{ds}} + \frac{V_f.\sin\delta}{X_{ds}}\right]$$

$$=\frac{3V_s^2 \cdot \sin 2\delta}{2X_{qs}} - \frac{3V_s^2 \cdot \sin 2\delta}{2X_{ds}} + \frac{3V_s V_f \cdot \sin\delta}{X_{ds}}$$

$$=\frac{3V_s V_f}{X_{ds}}\cdot\sin\delta + \frac{3V_s^2(X_{ds}-X_{qs})}{2X_{ds}X_{qs}}.\sin 2\delta \quad .....(6)$$

The power delivered to the shaft can be related with the torque developed in the motor.

Shaft Power $P_s = \left(\frac{2}{p}\right)\omega_e T_e$ .....(7)

If motor losses are ignored, the power input P_i is directly delivered to the shaft.

$\therefore P_s = P_i = \left(\frac{2}{p}\right)\omega_e T_e$

So, $P_i = \left(\frac{2}{p}\right)\omega_e T_e$ .....(8)

From equation (8), $T_e = \left(\frac{p}{2}\right)\times\left(\frac{1}{\omega_e}\right)\times p_i$ .....(9)

Substitute equation (6) in equation (9),

$$T_e = \left(\frac{p}{2}\right)\times\left(\frac{1}{\omega_e}\right)\times\left[\frac{3V_s V_f}{X_{ds}}.\sin\delta + \frac{3V_s^2(X_{ds}-X_{qs})}{2X_{ds}X_{qs}}.\sin 2\delta\right]$$

$$=3\times\left(\frac{p}{2}\right)\times\left(\frac{1}{\omega_e}\right)\times\left[\frac{V_s V_f}{X_{ds}}.\sin\delta + \frac{V_s^2(X_{ds}-X_{qs})}{2X_{ds}X_{qs}}.\sin 2\delta\right] \quad .....(10)$$

$$\psi_s = \left|\frac{V_s}{\omega_e}\right|$$

Considering only magnitude,

$V_s = \psi_s \cdot \omega_e$ .....(11)

Similarly, $V_f = \psi_f\,\omega_e$ .....(12)

The synchronous reactance X_s can be expressed as,

$X_s = \omega_e L_s$ .....(13)

$\therefore X_{ds} = \omega_e L_{ds}$ .....(14)

and $X_{qs} = \omega_e L_{qs}$ .....(15)

Substitute equation (11), equation (12), equation (14) and equation (15) in equation (10),

$$T_e = 3\times\left(\frac{p}{2}\right)\left(\frac{1}{\omega_e}\right)\times\left[\frac{\psi_s\omega_e\cdot\psi_f\,\omega_e}{\omega_e L_{ds}}.\sin\delta + \psi_s^2\omega_e^2.\frac{(\omega_e L_{ds}-\omega_e L_{qs})}{2\omega_e^2 L_{ds}L_{qs}}.\sin 2\delta\right]$$

$$=3\times\left(\frac{p}{2}\right)\times\left[\frac{\omega_e^2\cdot\psi_s\omega_f}{\omega_e^2 L_{ds}}.\sin\delta + \frac{\psi_s^2\omega_e^2}{\omega_e}\,\frac{\omega_e(L_{ds}-L_{qs})}{2\omega_e^2 L_{ds}L_{qs}}.\sin 2\delta\right]$$

$$\therefore T_e = 3\times\left(\frac{p}{2}\right)\left[\frac{\psi_s\omega_f}{L_{ds}}.\sin\delta + \frac{\psi_s^2(L_{ds}-L_{qs})}{2L_{ds}L_{qs}}.\sin 2\delta\right] \quad .....(16)$$

The 1st component of the equation is contributed by the field ψ_f. The 2nd component is defined as reluctance torque, which arises due to rotor saliency, i.e., $X_{ds} \neq X_{qs}$. Where the rotor tends to align with the position of minimum reluctance and is not influenced by the field excitation.

So, the developed torque of the synchronous reluctance motor is,

$$T_e = 3\times\left(\frac{p}{2}\right)\times\left[\frac{\psi_s^2(L_{ds}-L_{qs})}{2L_{ds}L_{qs}}.\sin 2\delta\right] \quad .....(17)$$

T_e is reluctance torque, with torque angle δ.

Slip- Torque Characteristics of Reluctance Motor

The starting torque depends upon the rotor position. The value of the starting torque varies between 300 to 400 % of its full load torque.

The motor operates at a constant speed up to a little over than 200% of its full load torque. If the loading of the motor is increased above the value of the pull out torque, the motor loose synchronism but continues to run as a single phase induction motor up to over 500% of its rated torque. At the starting the motor is subjected to Cogging. This can be reduced by skewing the rotor bars and by having the rotor slots not exact multiples of the number of poles.

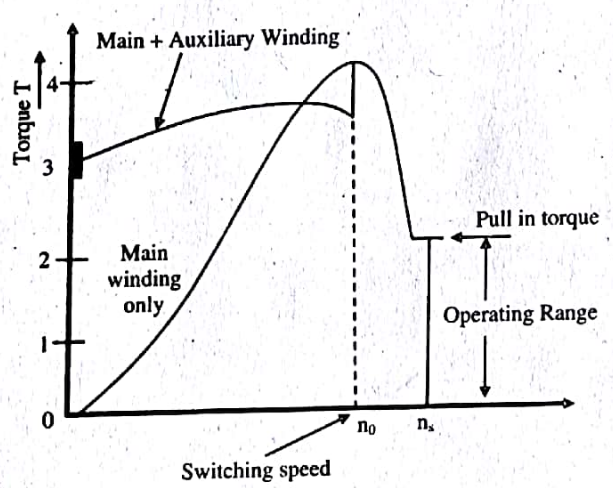


Figure 4.4

SWITCHED RELUCTANCE MOTOR

Ques 3) What do you mean by switched reluctance motor? Explain construction and principle of operation of switched reluctance motor.

Ans: Switched Reluctance Motor

Switched Reluctance Motor (SRM) is also known as Variable Reluctance Motor. This motor works on the principle of variable reluctance. This means, the rotor always tries to align along the lowest reluctance path. As the name suggests, a switching inverter is required for the operation of Switched Reluctance Motor.

Construction

Variable Reluctance Motor or Switched Reluctance Motor has two different constructions – Singly Salient Construction and Doubly Salient Construction. Stator and rotor magnetic circuits are laminated to reduce the core losses in both type of SRM.

1) **Singly Salient Construction:** A singly salient construction SRM comprises of a non-salient stator and a salient two pole rotor. The rotor do not have any winding wound over it but the stator have two phase winding as shown in **figure 4.5**.

It should be noted that, in actual SRM the number of phase winding on stator may be more than two. Since the rotor is of salient construction, the inductance of stator phase winding varies with the rotor position. The inductance is minimum when the rotor axis and stator phase winding axis coincides whereas it is maximum when both the axis are in quadrature.

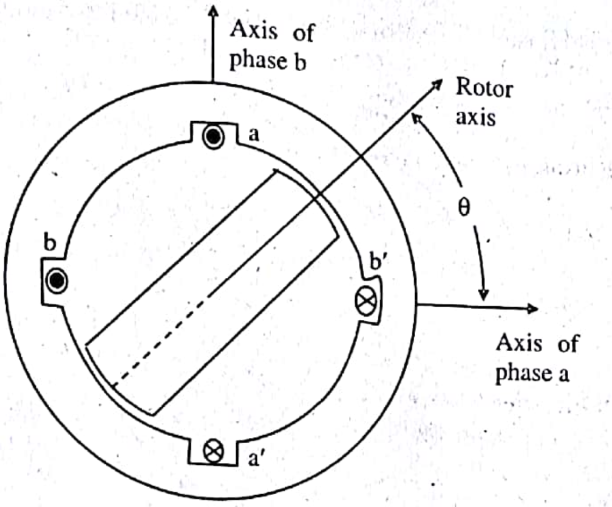


Figure 4.5

2) **Doubly Salient Construction:** Unlike singly salient type, the stator of doubly salient Switched Reluctance Motor is of salient construction and consists of four poles as shown in **figure 4.6**. The rotor do not carry any winding and is of salient construction but have two poles. Thus this type of SRM is a hetropolar motor where the numbers of stator and rotor poles are not same.

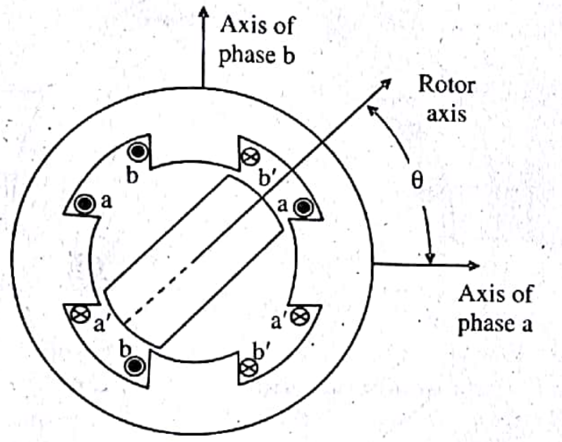


Figure 4.6

The stator phase windings are concentrated winding. These concentrated windings on radially opposite poles are either connected in series or parallel to result into two phase winding on stator. A doubly salient type Switched Reluctance Motor or Variable Reluctance Motor produces more torque as compared to singly salient type for the same size. Therefore a doubly SRM is more common and widely used.

Principle of Operation

The magnetic flux have a tendency to flow through lowest reluctance path, therefore rotor always tends to align along the minimum reluctance path. This is the basic working principle of Switched Reluctance Motor or Variable Reluctance Motor. Therefore, when stator phase winding A is energised, the rotor align along this phase as shown in **figure 4.7**.

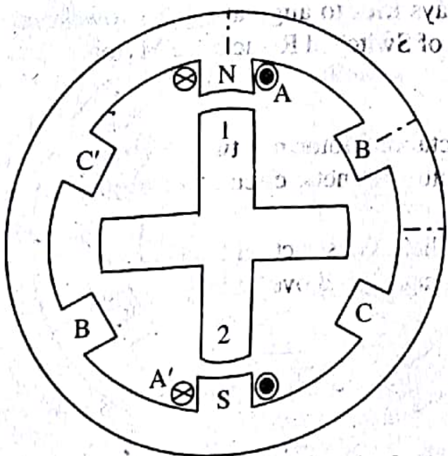


Figure 4.7: A Phase Energised

When stator phases winding A is de-energised and winding B is energised, the rotor aligns itself along B phase as shown in **figure 4.8.**

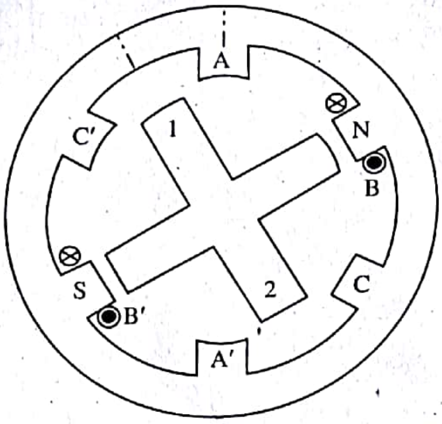


Figure 4.8: B Phase Energised

Similarly, the rotor occupies a position along phase winding C when this phase is energised.

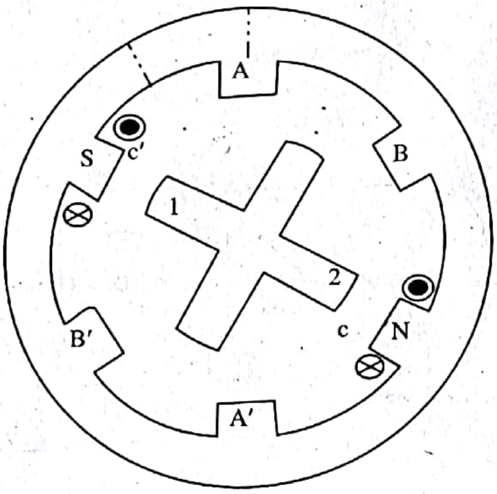


Figure 4.9: C Phase Energised

Thus rotor rotation in clockwise direction is achieved by energising the phase winding in a ABC sequence. If rotor rotation in anti-clockwise direction is require, stator phase winding must be energised in ACB sequence.

It must also be noted that, a particular phase winding must be energised/de-energised in synchronism with rotor position. This means as soon as the rotor align along the A phase, B phase must be energised and A phase must be de-energised if clockwise rotor rotation is required. To better understand the working principle, carefully observe the animation of Switched Reluctance Motor given in **figure 4.10**.

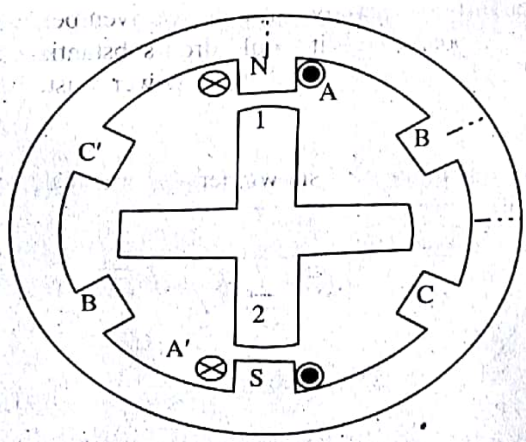


Figure 4.10

Ques 4) What is a power converter circuit? Write its different types.

Ans: Power Converter Circuits

A power converter is an electrical circuit that changes the electric energy from one form into the desired form optimised for the specific load. A converter may do one or more functions and give an output that differs from the input.

Types of Power Converter Circuits

There are following types of power converter circuits:

1) **Buck" converter circuit:** The schematic diagram shown here is for a "buck" converter circuit, a type of DC-DC "switching" power conversion circuit.

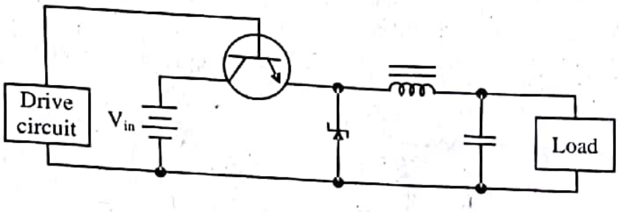


Figure 4.11

In this circuit, the transistor is either fully on or fully off; that is, driven between the extremes of saturation or cutoff. By avoiding the transistor's "active" mode (where it would drop substantial voltage while conducting current), very low transistor power dissipations can be achieved. With little power wasted in the form of heat, "switching" power conversion circuits are typically very efficient.

2) **Boost" converter circuit:** The schematic **figure 4.12** shown here is for a "boost" converter circuit, a type of DC-DC "switching" power conversion circuit

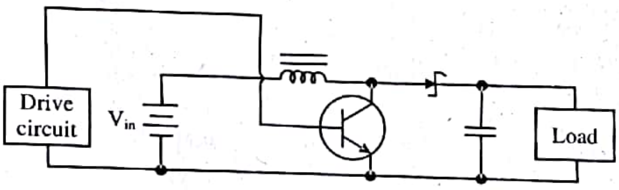


Figure 4.12

In this circuit, the transistor is either fully on or fully off; that is, driven between the extremes of saturation or cutoff. By avoiding the transistor's "active" mode (where it would drop substantial voltage while conducting current), very low transistor power dissipations can be achieved. With little power wasted in the form of heat, "switching" power conversion circuits are typically very efficient.

3) **Inverting" converter circuit**: The schematic **figure 4.13** shown here is for an "inverting" converter circuit, a type of DC-DC "switching" power conversion circuit.

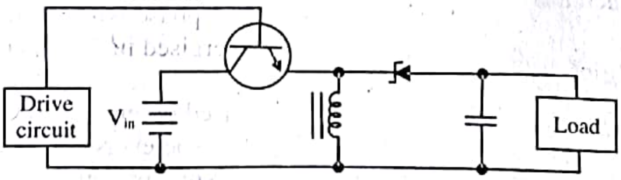


Figure 4.13

In this circuit, the transistor is either fully on or fully off; that is, driven between the extremes of saturation or cutoff. By avoiding the transistor's "active" mode (where it would drop substantial voltage while conducting current), very low transistor power dissipations can be achieved. With little power wasted in the form of heat, switching" power conversion circuits are typically very efficient.

4) **Cuk" converter circuit:** The schematic **figure 4.14** shown here is for a "Cuk" converter circuit, a type of DC-DC "switching" power conversion circuit.

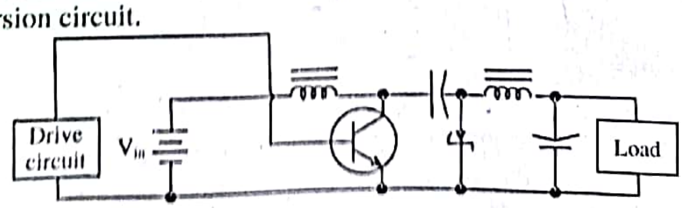


Figure 4.14

In this circuit, the transistor is either fully on or fully off; that is, driven between the extremes of saturation or cut off. By avoiding the transistor's "active" mode (where it would drop substantial voltage while conducting current), very low transistor power dissipations can be achieved. With little power wasted in the form of heat, "switching" power conversion circuits are typically very efficient.

Ques 5) Derive torque equation of switched reluctance motor with suitable diagram.

Ans: Torque Equation of Switched Reluctance Motor

From figure 4.15:

$$V = iR + \frac{d\lambda}{dt} \quad .....(1)$$

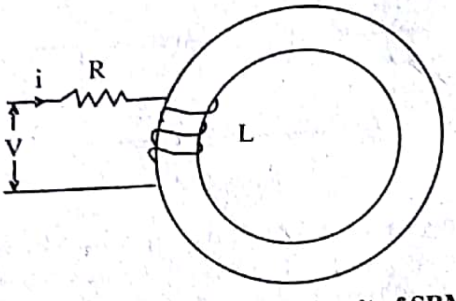


Figure 4.15: Basic R-L Circuit of SRM

Where, λ is a function of θ and L.

$$\frac{d\lambda}{dt} = \frac{d}{dt}i + \frac{di}{dt}\theta \quad .....(2)$$

$$V = iR + \frac{d(Li)}{dt} \quad .....(3)$$

$$= iR + L\frac{d}{dt} + i\frac{dL}{dt}$$

$$= iR + L\frac{di}{dt} + i\frac{dL}{d} \times \frac{d}{dt} \quad .....(4)$$

$$V = iR + L\frac{di}{dt} + i\omega\frac{dL}{d} \quad .....(5)$$

Where iR = ohmic drop

$L\frac{di}{dt}$ = emf due to incremental inductance

$i\omega\frac{dL}{d}$ = self-induced emf e or self emf

$$V = iR + L\frac{di}{dt} + e \quad .....(6)$$

Self-induced emf e is proportional to current speed and rate of change of inductance with rotor angle.

If flat topped current is assumed $L\frac{di}{dt} = 0$ on the other hand if the inductance is constant, self emf is zero. So the first term $L\frac{di}{dt}$ absorbs all the applied voltage.

$$Vi = i^2R + L\frac{di}{dt} + i^2\omega\frac{dL}{d} \quad .....(7)$$

Energy stored in the magnetic circuit = $\frac{1}{2}Li^2$

Rate of change of energy stored in the magnetic circuit = $\frac{d}{dt}\left[\frac{1}{2}Li^2\right]$ .....(8)

$$= \frac{1}{2}L.2i\frac{di}{dt} + \frac{1}{2}i^2\frac{dL}{dt}$$

$$= Li\frac{di}{dt} + \frac{1}{2}i^2\frac{dL}{d} \times \frac{d}{dt}$$

$$\frac{dW_{mag}}{dt} = Li\frac{di}{dt} + \frac{1}{2}i^2\omega\frac{dL}{d} \qquad .....(9)$$

Mechanical energy transferred = electrical energy input i^2R rate of change of energy stored in the magnetic circuit.

$$\text{Mechanical energy transferred} = Vi \cdot i^2R \cdot \frac{dW_{mag}}{dt}$$

$$= i^2R + Li\frac{di}{dt} + i^2\omega\frac{dL}{d} i^2R.Li\frac{di}{dt}\frac{1}{2}i^2\omega\frac{dL}{d}$$

$$P_m = \frac{1}{2}i^2\omega\frac{dL}{d} \qquad .....(10)$$

$$P_m = \omega T \qquad .....(11)$$

$$\therefore \text{ Torque } T = \frac{1}{2}i^2\frac{dL}{d} \qquad .....(12)$$

Ques 4: Give the comparison between switched reluctance and reluctance motor.

Or

Write application of Switched Reluctance Motor.

Ans: Comparison between Switched Reluctance and Reluctance Motor.

Switched Reluctance Motor	Reluctance Motor
The conduction angle for phase currents is controlled and synchronised with the rotor position, usually by means of a shaft position sensor.	Construction is simple and robust, as there is no brush.
SR motor is designed for efficient power conversion at high speeds comparable with those of the PM brushless dc motor.	No permanent magnet, neither in the stator nor in the rotor.
SR motor is more than a high-speed Reluctance motor.	It is impossible to have very high speeds.
Its performance and low manufacturing cost make it a competitive motor to PM brushless dc system.	Rotor carries no windings, no slip rings and brush-less maintenance.

Application of Switched Reluctance motor

1) Washing machine,
2) Vacuum cleaner,
3) Fans,
4) Future automobile application, and
5) Robotic control application.

Module 5

Permanent Magnet DC Motors

PERMANENT MAGNET DC MOTORS

Ques 1) What do you mean by permanent magnet DC Motors? Explain construction and principle of working of permanent magnet DC motor.

Ans: Permanent Magnet DC motor
A DC Motor whose poles are made of Permanent Magnets is known as Permanent Magnet DC (PMDC) motor. The magnets are radially magnetised and are mounted on the inner periphery of the cylindrical steel stator. The stator of the motor serves as a return path for the magnetic flux. The rotor has a DC armature, with commutator segments and brushes.

Construction
As it is indicated in name of permanent magnet DC motor, the field poles of this motor are essentially made of permanent magnet. A PMDC motor mainly consists of two parts – a stator and an armature. Here the stator which is a steel cylinder. The magnets are mounted in the inner periphery of this cylinder.

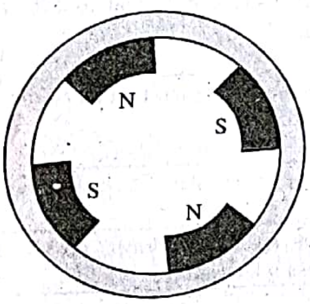


Figure 5.1

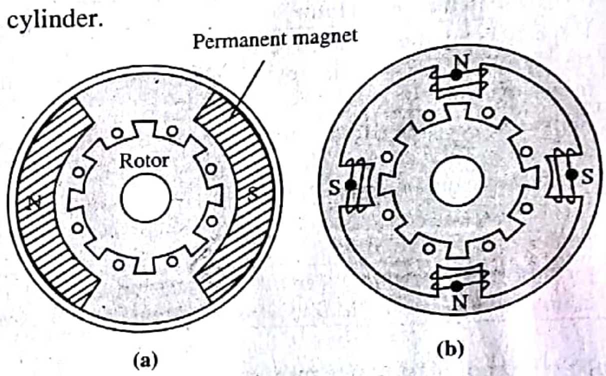


Figure 5.2

The permanent magnets are mounted in such a way that the N-pole and S-pole of each magnet are alternatively faced towards armature as shown in the **figure 5.2**. That means, if N-pole of one magnet is faced towards armature then S-pole of very next magnet is faced towards armature. In addition to holding the magnet on its inner periphery, the steel cylindrical stator also serves as low reluctance return path for the magnetic flux.

Although field coil is not required in permanent magnet DC motor but still it is sometimes found that they are used along with permanent magnet. This is because if permanent magnets lose their strength, these lost magnetic strengths can be compensated by field excitation through these field coils. Generally, rare earth hard magnetic materials are used for these permanent magnet.

The rotor of PMDC motor is similar to other DC motor. The rotor or armature of permanent magnet DC motor also consists of core, windings and commutator. Armature core is made of number of varnish insulated, slotted circular lamination of steel sheets.

By fixing these circular steel sheets one by one, a cylindrical shaped slotted armature core is formed. The varnish insulated laminated steel sheets are used to reduce eddy current loss in armature of permanent magnet DC motor. These slots on the outer periphery of the armature core are used for housing armature conductors in them. The armature conductors are connected in a suitable manner which gives rise to armature winding. The end terminals of the winding are connected to the commutator segments placed on the motor shaft. Like other DC motor, carbon or graphite brushes are placed with spring pressure on the commutator segments to supply current to the armature.

Principle of Working
In a DC motor, an armature rotates inside a magnetic field. Basic working principle of DC motor is based on the fact that whenever a current carrying conductor is placed inside a magnetic field, there will be mechanical force experienced by that conductor.

As we said earlier the working principle of PMDC motor is just similar to the general working principle of DC motor. That is when a carrying conductor comes inside a magnetic field, a mechanical force will be experienced by the conductor and the direction of this force is governed by Fleming's left hand rule. As in a permanent magnet DC motor, the armature is placed inside the magnetic field of permanent magnet; the armature rotates in the direction of the generated force. Here each conductor of the armature experiences the mechanical force F = B.I.L. Newton where, B is the magnetic field strength in Tesla (weber/m2), I is the current in Ampere flowing through that conductor and L is length of the conductor in metre comes under the magnetic field. Each conductor of the armature experiences a force and the compilation of those forces produces a torque, which tends to rotate the armature.

Ques 2) Draw and explain equivalent circuit of permanent magnet DC motor.

Ans: Equivalent Circuit of Permanent Magnet DC Motor or PMDC Motor

As in PMDC motor the field is produced by permanent magnet, there is no need of drawing field coils in the equivalent circuit of permanent magnet DC motor. The supply voltage to the armature will have armature resistance drop and rest of the supply voltage is countered by back emf of the motor. Hence voltage equation of the motor is given by,

$$V = IR + E_b$$

Where, I is armature current and R is armature resistance of the motor. Eb is the back emf and V is the supply voltage.

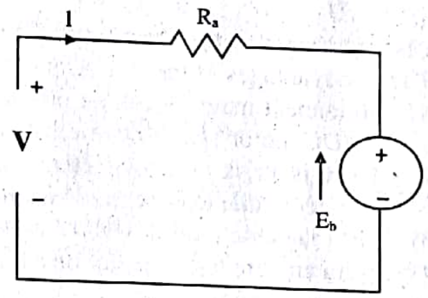


Figure 5.3

In conventional DC motor, the generated or back EMF is given by the equation shown below:

$$E = k \phi N \quad .....(1)$$

The electromagnetic torque is given as

$$T_e = k \phi I_a \quad .....(2)$$

In Permanent Magnet DC motor, the value of flux ϕ is constant. Therefore, the above equation (1) and (2) becomes

$$E = k_1 N \quad .....(3)$$

$$T_e = k_1 I \quad .....(4)$$

Considering the above circuit diagram the following equations are expressed:

$$V = E + I_a R_a \quad .....(5)$$

Putting the value of E from the equation (3) in equation (5) we get,

$$V = k_1 N + I_a R_a \quad \text{or}$$

$$N = \frac{V - I_a R}{k_1} \quad .....(6)$$

Where, $k_1 = k \phi$ and is known as speed-voltage constant or torque constant. Its value depends upon the number of field poles and armature conductors.

The speed control of the PMDC motor cannot be controlled by using flux control method as the flux remains constant in this type of motor. Both speed and torque can be controlled by armature voltage control, armature rheostat control, and chopper control methods. These motors are used where the motor speed below the base speed is required as they cannot be operated above the base speed.

Ques 3) Explain different types of permanent magnet materials and also write the advantages and disadvantages of PMDC.

Ans: Types of Permanent Magnet Materials

There are three types of Permanent Magnet Materials used in PMDC Motor which is explained as follows:

1) **Alnicos:** Alnicos has a low coercive magnetizing intensity and high residual flux density. Hence, it is used where low current and high voltage is required.
2) **Ferrites:** They are used in cost sensitive applications such as Air conditioners, compressors, and refrigerators.
3) **Rare earths:** Rare earth magnets are made of Samarium cobalt, neodymium-iron-boron. They have a high residual flux and high coercive magnetizing intensity. The rare earth magnets are exempted from demagnetizing problems due to armature reaction. It is an expensive material.

4) The Neodymium iron boron is cheaper as compared to Samarium cobalt. But it can withstand higher temperature. Rare earth magnets are used for size-sensitive applications. They are used in automobiles, servo industrial drives and in large industrial motors.

Advantages of the Permanent Magnet DC Motor

Following are the advantages of the PMDC Motor.

1) They are smaller in size.
2) For smaller rating Permanent Magnet reduces the manufacturing cost and thus PMDC motor are cheaper.
3) As these motors do not require field windings, they do not have field circuit copper losses. This increases their efficiency.

Disadvantages of the Permanent Magnet DC Motor

The disadvantages of the PMDC motor are given below:

1) Permanent magnets cannot produce a high flux density as that as an externally supplied shunt field does. Therefore, a PMDC motor has a lower induced torque per ampere turns of armature current then a shunt motor of the same rating.
2) There is a risk of demagnetization of the poles which may be caused by large armature currents. Demagnetization can also occur due to excessive heating and also when the motor is overloaded for a long period of time.
3) The magnetic field of PMDC motor is present at all time, even when the motor is not being used.
4) Extra ampere turns cannot be added to reduce the armature reaction.

Ques 4) Sketch the characteristics and write applications of permanent magnet DC motor.

Ans: Characteristics of PMDC

Characteristics of PMDC motors are similar to the characteristics of dc shunt motor in terms of torque, speed and armature current. However, speed-torque characteristics are more linear and predictable in PMDC motors.

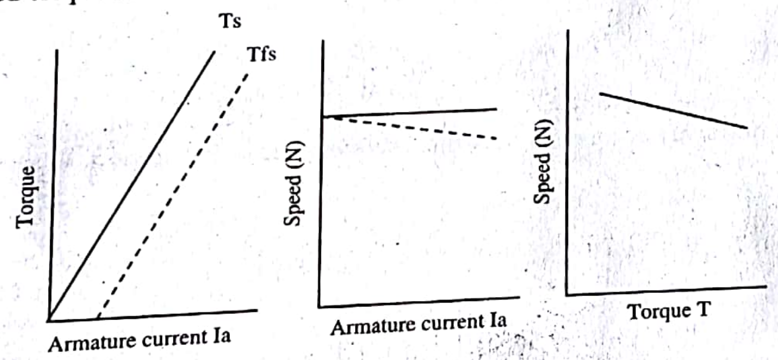


Figure 5.4

Applications of the Permanent Magnet DC Motor

The PMDC motors are used in various applications ranging from fractions to several horsepower. They are developed up to about 200 kW for use in various industries. The following applications are given below:

1) PMDC motors are mainly used in automobiles to operate windshield wipers and washers, to raise the lower windows, to drive blowers for heaters and air conditioners etc.
2) They are also used in computer drives.
3) These types of motors are also used in toy industries.
4) PMDC motors are used in electric toothbrushes, portable vacuum cleaners, and food mixers.
5) Used in a portable electric tool such as drilling machines, hedge trimmers etc.

BRUSHLESS DC MOTORS

Ques 5) What do you mean by brushless DC motor? Explain construction and principle of working of brushless DC Motors.

Ans: Brushless DC Motor

Brushless DC motor may be described as an electronically commuted motor which does not have brushes. These types of motors are highly efficient in producing a large amount of torque over a vast speed range. In brushless motors, permanent magnets rotate around a fixed armature and overcome the problem of connecting current to the armature. Commutation with electronics has a large scope of capabilities and flexibility. They are known for smooth operation and holding torque when stationary.

Construction

A brushless DC motor consists of a rotor in form of a permanent magnet and stator in form of polyphase armature windings. It differs from conventional DC motor in such that it doesn't contains brushes and the commutation is done using electrically

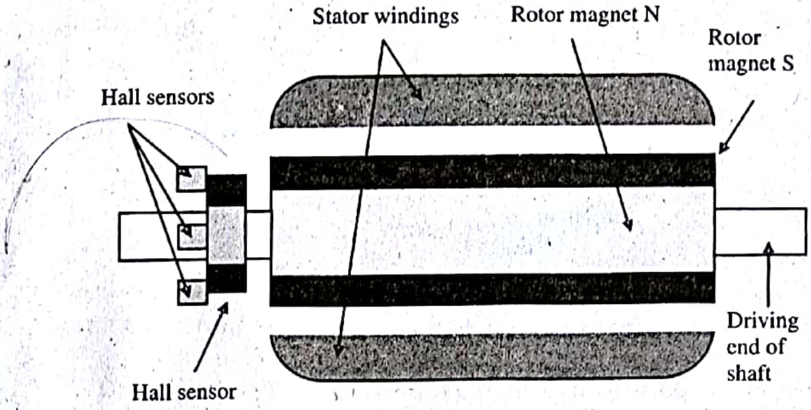


Figure 5.5

Brushless DC Motor has:

1) A rotor with permanent magnets and a stator with windings
2) A BLDC motor is essentially a DC motor turned inside out
3) Brushes and commutator have been eliminated and the windings are connected to the control electronics
4) Control electronics replace the function of the commutator and energize the proper winding
5) Windings are energized in a pattern which rotates around the stator .
6) The energized stator winding leads the rotor magnet and switches just as the rotor aligns with the stator

Brushless DC motor has only two basic parts – rotor and the stator. The rotor is the rotating part and has rotor magnets whereas stator is the stationary part and contains stator windings. In BLDC permanent magnets are attached in the rotor and move the electromagnets to the stator. The high power transistors are used to activate electromagnets for the shaft turns. The controller performs power distribution by using a solid-state circuit.

Basically a BLDC motor can be constructed in two ways – by placing the rotor outside the core and the windings in the core and another by placing the windings outside the core. In the former arrangement, the rotor magnets act as an insulator and reduce the rate of heat dissipation from the motor and operate at low current. It is typically used in fans. In the latter arrangement, the motor dissipates more heat, thus causing an increase in its torque. It is used in hard disk drives.

Principle of Working

In brushes motors, there are permanent magnets on the outside and a spinning armature which contains electromagnet is inside. These electromagnets create a magnetic field in the armature when power is switched on and help to rotates armature. The brushes change the polarity of the pole to keep the rotation on of the armature. The basic principles for the brushed DC motor and for brushless DC motor are same, i.e., internal shaft position feedback.

Ques 6). Explain types of brushless DC motor.

Ans: Types of Brushless DC Motors

Basically, BLDC are of two types, one is outer rotor motor and other is inner rotor motor. The basic difference between the two is only in designing, their working principles are same.

1) **Inner Rotor Design:** In an inner rotor design, the rotor is located in the centre of the motor and the stator winding surround the rotor. As the rotor is located in the core, rotor magnets do not insulate heat inside and heat get dissipated easily. Due to this reason, inner rotor designed motor produces a large amount of torque and validly used.

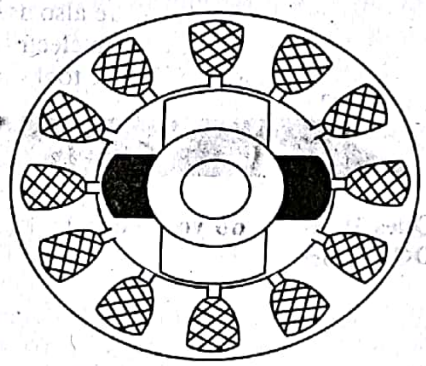


Figure 5.6: Inner Motor

2) **Outer Rotor Design:** In outer rotor design, the rotor surrounds the winding which is located in the core of the motor. The magnets in the rotor trap the heat of the motor inside and do not allow to dissipate from the motor. Such type of designed motor operates at lower rated current and has low cogging torque.

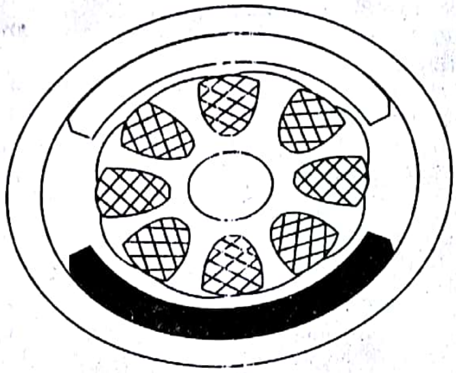


Figure 5.7: Outer Motor

Ques 7) Discuss about operation of 4 Pole 2 Phase brushless DC motor.

Ans: Operation of 4 Pole 2 Phase Motor brushless DC motor
The brushless DC motor is driven by an electronic drive which switches the supply voltage between the stator windings as the rotor turns. The rotor position is monitored by the transducer (optical or magnetic) which supplies information to the electronic controller and based on this position, the stator winding to be energized is determined. This electronic drive consists of transistors (2 for each phase) which are operated via a microprocessor.

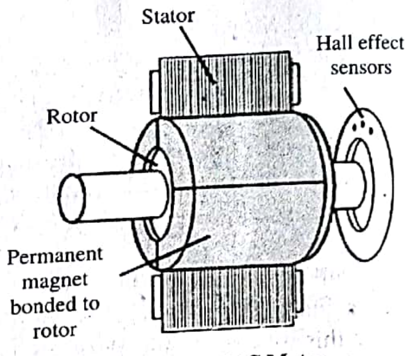


Figure 5.8: BLDC Motor

In a 4 pole, 2 phase brushless DC motor, a single hall sensor is used, which is embedded on the stator. As the rotor rotates, the hall sensor senses the position and develops a high or low signal, depending on the pole of the magnet (North or South). The hall sensor is connected via a resistor to the transistors. When a high voltage signal occurs at the output of the sensor, the transistor connected to coil A starts conducting, providing the path for the current to flow and thus energizing coil A.

The capacitor starts charging to the full supply voltage. When the hall sensor detects a change in polarity of the rotor, it develops a low voltage signal at its output and since the transistor 1 doesn't get any supply, it is in cutoff condition. The voltage developed around the capacitor is Vcc, which is the supply voltage to the 2nd transistor and coil B is now energized, as current passes through it.

BLDC motors have fixed permanent magnets, which rotate and a fixed armature, eliminating the problems of connecting current to the moving armature. And possibly more poles on the rotor than the stator or reluctance motors. The latter may be without permanent magnets, just poles that are induced on the rotor then pulled into arrangement by timed stator windings.

An electronic controller replaces the brush/commutator assembly of the brushed DC motor, which continually switches the phase to the windings to keep the motor turning. The controller performs comparative timed power distribution by using a solid-state circuit instead of the brush/commutator system.

Ques 8) Why do brushless DC motor (BLDC Motors) Turn?

Ans: As their name implies, brushless DC motors do not use brushes. With brushed motors, the brushes deliver current through the commutator into the coils on the rotor. Instead, the rotor is a permanent magnet; the coils do not rotate, but are instead fixed in place on the stator. Because the coils do not move, there is no need for brushes and a commutator. **(Figure 5.9)**

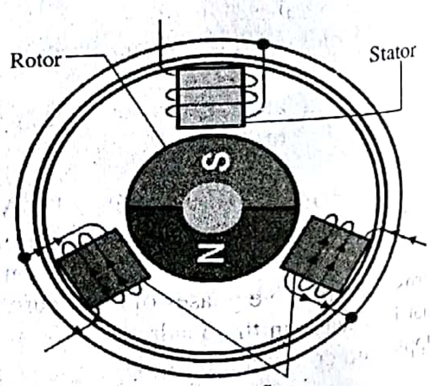


Figure 5.9: BLDC Motor

With the brushed motor, rotation is achieved by controlling the magnetic fields generated by the coils on the rotor, while the magnetic field generated by the stationary magnets remains fixed. To change the rotation speed, you change the voltage for the coils. With a BLDC motor, it is the permanent magnet that rotates; rotation is achieved by changing the direction of the magnetic fields generated by the surrounding stationary coils. To control the rotation, you adjust the magnitude and direction of the current into these coils. Since the rotor is a permanent magnet, it needs no current, eliminating the need for brushes and commutator. Current to the fixed coils is controlled from the outside.

Ques 9) Explain trapezoidal type and sinusoidal type brushless DC motor and sketch the output waveform.

OR

Write applications of brushless DC motor.

Ans: Trapezoidal Type Brushless DC Motor

One of the simplest methods of control for DC brushless motors uses what is termed Trapezoidal commutation. Figure 5.10 illustrates the block diagram of Trapezoidal type brushless DC motor.

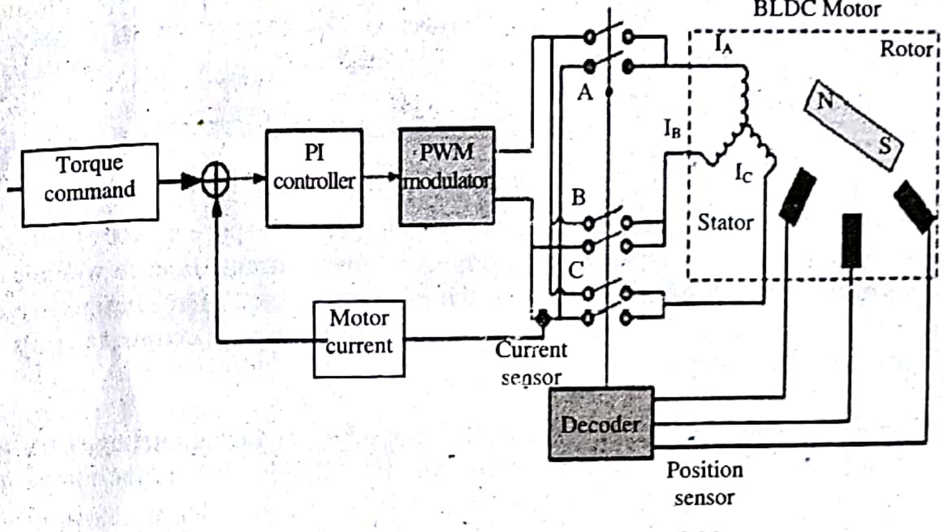


Figure 5.10: Trapezoidal Type Brushless DC Motor

In this scheme, current is controlled through motor terminals one pair at a time, with the third motor terminal always electrically disconnected from the source of power.

Three Hall devices embedded in the motor are usually used to provide digital signals which measure rotor position within 60 degree sectors and provide this information to the motor controller. Because at any time, the currents in two of the windings are equal in magnitude and the third is zero, this method can only produce current space vectors having one of six different directions. As the motor turns, the current to the motor terminals is electrically switched (commutated) every 60 degrees of rotation so that the current space vector is always within the nearest 30 degrees of the quadrature direction.

The current waveform for each winding is therefore a staircase from zero, to positive current, to zero, and then to negative current. This produces a current space vector that approximates smooth rotation as it steps among six distinct directions as the rotor turns.

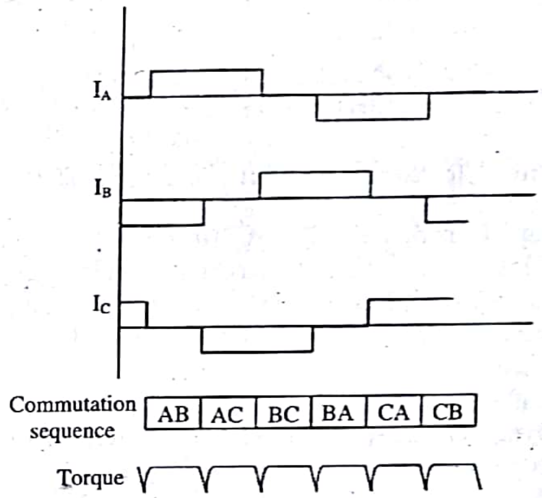


Figure 5.11

In motor applications such as air conditioners and refrigerators use of Hall-Effect sensors is not a viable option. Back-EMF sensors that sense the back EMF in the unconnected winding can be used to achieve the same results.

The trapezoidal-current drive systems are popular because of the simplicity of their control circuits but suffer from a torque ripple problem during commutation.

Ques 10) Explain the sinusoidal type brushless DC motor and also write the expression of torque shaft of sinusoidal brushless DC motor.

Ans: Sinusoidal Type Brushless DC Motor

Figure 5.12 shows the block diagram of sinusoidal type brushless DC motor. Sinusoidally commutated brushless motor controllers attempt to drive the three motor windings with three currents that vary smoothly and sinusoidally as the motor turns. The relative phases of these currents are chosen so that they should result in a smoothly rotating current space vector that is always in the quadrature direction with respect to the rotor and has constant magnitude. This eliminates the torque ripple and commutation spikes associated with trapezoidal commutation.

In order to generate smooth sinusoidal modulation of the motor currents as the motor turns, an accurate measurement of rotor position is required. The Hall devices provide only a coarse measure of rotor position and are inadequate for this purpose. For this reason, angle feedback from an encoder, or similar device, is required.

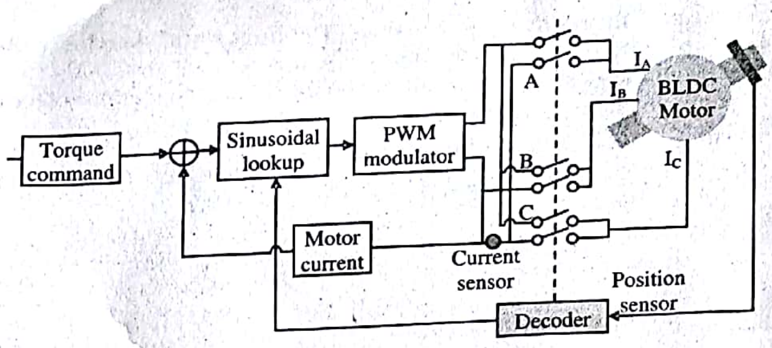


Figure 5.12: Sinusoidal Type Brushless DC Motor

Since the winding currents must combine to produce a smoothly rotating current space vector of constant magnitude, and because the stator windings are oriented 120 degrees apart from each other, currents in each winding must be sinusoidal and phase shifted by 120 degrees. Position information from the encoder is used to synthesize two sinusoids, one 120 degrees phase shifted from the other. These signals are then multiplied by the torque command so that the amplitudes of the sine waves are proportional to desired torque.

The result is two sinusoidal current command signals appropriately phased to produce a rotating stator current space vector in the quadrature direction. Sinusoidal commutation solves this problem. This is because the torque produced in a three phase brushless motor (with a sine wave back-EMF) is defined by the following equation:

Shaft Torque = Kt [IR Sinθ + IS Sin (θ+120) + IT Sin (θ+240)]

Where,

θ, is the electrical angle of the shaft,
Kt is the torque constant of the motor and
IR, I S and I T are the phase currents.

Ques 11) Discuss in detail about controlling of BLDC motor.

Ans: Controlling a BLDC Motor
Control unit is implemented by microelectronic has several high-tech choices. This may be implemented using a micro-controller, a dedicated micro-controller, a hard-wired microelectronic unit, a PLC or similar other unit. Analog controller are still using, but the BLDC motor cannot process feedback messages and control accordingly. With this type of control circuits it is possible to implements high performance control algorithms, such as vector control, field oriented control, high speed control all of which are related to electromagnetic state of the motor. Furthermore outer loop control for various dynamics requirements such as sliding motor controls, adaptive control, predictive control…etc are also implemented conventionally.

Beside all these, we find high performance PIC (Power Integrated Circuit), ASIC (Application Specific Integrated Circuits) …etc. that can greatly simplify the construction of the control and the power electronic unit both. For example, today we have complete PWM (Pulse Width Modulation) regulator in a single IC that can be replace the entire control unit in some systems. Compound driver IC can provide the complete solution of driving all six power switches in a three phase converter. There are numerous similar integrated circuits with more and more adding day by day. At the end of the day, system assembly will possibly involve only a piece of control software with all hardware coming the right shape and form. PWM (Pulse Width Modulation) wave can be used to control the speed of the motor.

Here the average voltage given or the average current flowing through the motor will change depending on the ON and OFF time of the pulses controlling the speed of the motor i.e. The duty cycle of the wave controls its speed. On changing the duty cycle (ON time), we can change the speed. By interchanging output ports, it will effectively change direction of the motor.

Ques 12) Explain the speed control of BLDC motor with its types.

Ans: Speed Control
Speed control of BLDC motor is essential for making the motor work at desired rate. Speed of a brushless dc motor can be controlled by controlling the input dc voltage. The higher the voltage, more is the speed. When motor works in normal mode or runs below rated speed, input voltage of armature is changed through PWM model. When motor is operated above rated speed, the flux is weakened by means of advancing the exiting current.

Types of Speed Control

The speed control can be closed loop or open loop speed control which is explained as follows:

1) **Open Loop Speed Control:** It involves simply controlling the dc voltage applied to motor terminals by chopping the DC voltage. However this results in some form of current limiting.
2) **Closed Loop Speed Control:** It involves controlling the input supply voltage through the speed feedback from the motor. Thus the supply voltage is controlled depending on the error signal.

   The closed loop speed control consists of three basic components.
   i) A PWM circuit to generate the required pwm pulses. It can be either a microcontroller or a timer IC.
   ii) A sensing device to sense the actual motor speed. It can be a hall effect sensor, a infrared sensor or a optical encoder.
   iii) A motor drive to control the motor operation.

This technique of changing the supply voltage based on the error signal can be either through PID controlling technique or using fuzzy logic.

Ques 13) What are Brushless DC Motors used for? Write the advantages disadvantages and applications of Brushless DC Motors.

Ans: Use of Brushless DC Motors

Brushless DC motors typically have an efficiency of 85-90%, while brushed motors are usually only 75-80% efficient. Brushes eventually wear out, sometimes causing dangerous sparking, limiting the lifespan of a brushed motor. Brushless DC motors are quiet, lighter and have much longer lifespans. Because computers control the electrical current, brushless DC motors can achieve much more precise motion control.

Because of all these advantages, brushless DC motors are often used in modern devices where low noise and low heat are required, especially in devices that run continuously. This may include washing machines, air conditioners and other consumer electronics. They may even be the main power source for service robots, which will require very careful control of force for safety reasons.

Brushless DC motors provide several distinct advantages over other types of electric motors, which is why they've made their way into so many household items and may be a major factor in the growth of service robots inside and outside of the industrial sector.

Advantages of Brushless DC Motor

1) Brushless motors are more efficient as its velocity is determined by the frequency at which current is supplied, not the voltage.
2) As brushes are absent, the mechanical energy loss due to friction is less which enhanced efficiency.
3) BLDC motor can operate at high-speed under any condition.
4) There is no sparking and much less noise during operation.
5) More electromagnets could be used on the stator for more precise control.
6) BLDC motors accelerate and decelerate easily as they are having low rotor inertia.
7) It is high performance motor that provides large torque per cubic inch over a vast sped rang.
8) BLDC motors do not have brushes which make it more reliable, high life expectancies, and maintenance free operation.
9) There is no ionizing sparks from the commutator, and electromagnetic interference is also get reduced.
10) Such motors cooled by conduction and no air flow are required for inside cooling.

Disadvantages of Brushless DC Motors

1) BLDC motor cost more than brushless DC motor.
2) The limited high power could be supplied to BLDC motor, otherwise too much heat weakens the magnets and insulation of winding may get damaged.

Application

1) Consumer electronics
2) Transport
3) Heating and ventilation
4) Industrial engineering
5) Model engineering.

Module 6

Linear Motors

LINEAR MOTORS

Ques 1) What do you mean by linear motor? Explain construction and principle of working of linear motor and also write the advantages and disadvantages of linear motor.

Ans: Linear Motors

Linear motors are electric induction motors that produce motion in a straight line rather than rotational motion. In a traditional electric motor, the rotor (rotating part) spins inside the stator (static part); in a linear motor, the stator is unwrapped and laid out flat and the "rotor" moves past it in a straight line. Linear motors often use superconducting magnets, which are cooled to low temperatures to reduce power consumption.

Construction of Linear Motor

Figure 6.1 illustrates the constructional diagram of linear motor. In a traditional DC electric motor, a central core of tightly wrapped magnetic material (known as the rotor) spins at high speed between the fixed poles of a magnet (known as the stator) when an electric current is applied. In an AC induction motor, electromagnets positioned around the edge of the motor are used to generate a rotating magnetic field in the central space between them. This induces (produces) electric currents in a rotor, causing it to spin. In an electric car, DC or AC motors like these are used to drive gears and wheels and convert rotational motion into motion in a straight line.

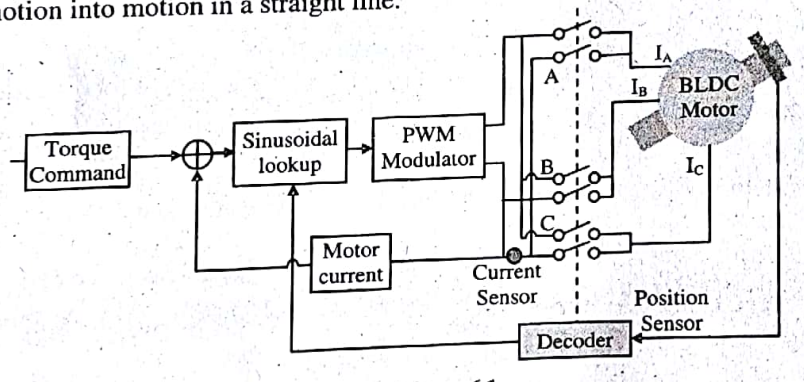


Figure 6.1

Principle of Working

A linear motor is effectively an AC induction motor that has been cut open and unwrapped. The stator is laid out in the form of a track of flat coils made from aluminum or copper and is known as the primary of a linear motor. The rotor takes the form of a moving platform known as the "secondary. When the current is switched on, the secondary glides past the primary supported and propelled by a magnetic field.

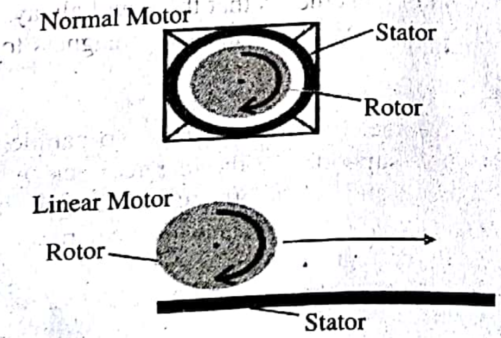


Figure 6.2

Linear motors operate with an AC power supply and servo controller, which are often the same as those used for rotary servo motors. The linear motor primary part is connected to the power supply to produce a magnet field. By changing the current phase in the coils, the polarity of each coil is changed. The attractive and repelling forces between the coils in the primary part and the magnets in the secondary part cause the primary to move and generate a linear force. The rate of change of the current controls the velocity of the movement, and the amperage of the current determines the force generated.

Advantages of Linear Motors

1) No mechanical contact, the transmission force is generated in the air gap, in addition to the linear motor rail without any other friction
2) The structure is simple, small size, by using fewer parts to achieve our linear drive, and this is only a moving part
3) The itinerary of the operation is theoretically unrestricted, and its performance will not be affected by the size of its itinerary
4) Its operation can provide a wide range of speed operating range, which covers from a few micrometers per second to several meters, especially in the high speed state is one of its outstanding advantages
5) Acceleration, larger up to 10g
6) Smooth movement, this is because in addition to supporting the role of linear guide or air bearing, there is no other mechanical connection or conversion device
7) Accuracy and repeatability is high, because the intermediate part of the accuracy is eliminated, the accuracy of the system depends on the position detection element, the appropriate feedback device can reach sub-micron level
8) Maintenance is simple, because the parts less, no mechanical contact when moving, thus greatly reducing the wear and tear parts, only little or no maintenance, longer life. Linear motor and "rotating motor, ball screw" transmission performance comparison table performance rotary motor + ball screw linear motor.

Disadvantages of Linear Motors:

1) Linear motor power consumption, especially in the high load, high acceleration of the movement, the machine instantaneous current on the workshop power supply system to bring heavy load;
2) is high vibration, linear motor dynamic stiffness is very low, cannot play the role of buffer damping, in high-speed movement easily lead to other parts of the machine resonance;
3) is a large amount of heat, fixed at the bottom of the table motor motor is a high fever parts, the installation location is not conducive to natural heat, the machine temperature control caused great challenges;
4) Is not self-locking, in order to ensure safe operation, linear motor-driven movement axis, especially the vertical movement axis, must be equipped with additional locking mechanism, increasing the complexity of the machine.

Ques 2) Describe all types of linear motor.

Ans: Types of Linear Motors

There are following types of linear motor

1) **Cylindrical Moving Magnet Linear Motors:** In these motors, the forcer is cylindrical and moves up and down a cylindrical bar that houses the magnets. These motors were among the first to find commercial application, but do not exploit all of the space saving characteristics of their flat and U-channel counterparts. The magnetic circuit is similar to that of a moving magnet actuator. The difference is that the coils are replicated to increase the stroke. The coil winding typically consists of three phases, with brushless commutation using Hall Effect devices.

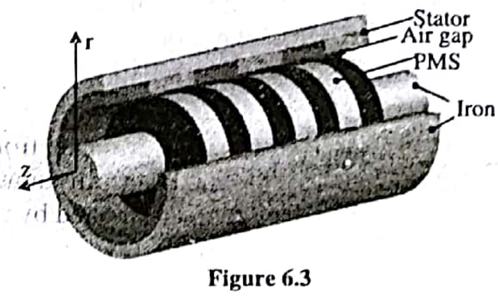


Figure 6.3

The forcer is circular and moves up and down the magnetic rod. This rod is not suitable for applications sensitive to the leakage of magnetic flux. Because the motor is completely circular and travels up and down the rod, the only points of support are at the ends. This means that there will always be a limit to length before the deflection in the bar causes the magnets to contact the forcer.

2) **U-Channel Linear Motor:** The U-channel linear motor has two parallel magnet tracks facing each other with the forcer between the plates. The forcer is supported in the magnet track by a bearing system. The forcers are ironless, which means there is no attractive force and no disturbance forces generated between forcer and magnet track. The ironless coil assembly has low mass, allowing for very high acceleration. Typically the coil winding is three phase, with brushless commutation. Increased performance can be achieved by adding air-cooling. This design is better suited to reduced magnetic flux leakage due to the magnets facing each other and being housed in a U-shaped channel. Due to the design of the magnet track, they can be added together to increase the length of travel, with the only limit being the length of the cable management system, encoder length available, and the ability to machine large, flat structures.

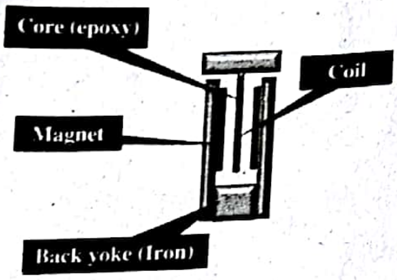


Figure 6.4

3) **Flat-Type Linear Motors:** There are three designs of these motors: slotless ironless, slotless iron, and slotted iron. Again, all types are brushless. To choose between these types of motors requires an understanding of the application. **Figure 6.5** shows that flat type linear moters.

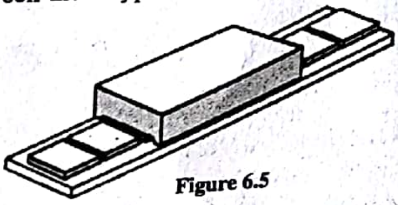


Figure 6.5

4) **Slotless-Ironless Flat Motors:** The slotless-ironless flat motor consists of a series of coils mounted to an aluminium base. Due to the lack of iron in the forcer, the motor has no attractive force or cogging, which helps with bearing life in certain applications. Forcers can be mounted from the top or sides to suit most applications. Ideal for smooth velocity control such as scanning applications, this type of design yields the lowest force output of flat-track designs. Generally, flat magnet tracks have high magnetic flux leakage. **Figure 6.6** shows that slotless-Ironless flat maters.

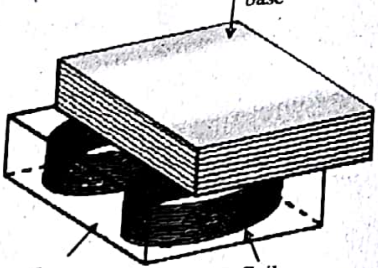


Figure 6.6

5) **Slotless-Iron Flat Motor:** The slotless-iron flat motor is similar in construction to the slotless-ironless motor except the coils are mounted to iron laminations and then to the aluminium base. Iron laminations are used to direct the magnetic field and increase the force. Due to the iron laminations, an attractive force is now present between the forcer and the track and is proportional to the force produced by the motor. As a result of the laminations, a cogging force is now present on the motor. This motor design produces more force than the ironless designs. **Figure 6.7** shows that shotless from flat motor.

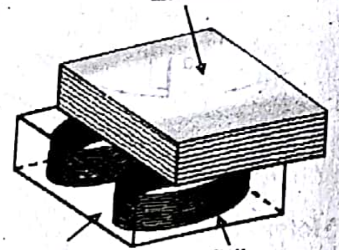


Figure 6.7

6) **Slotted-Iron Flat Motors:** In this type of linear motor, the coil windings are inserted into a steel structure to create the coil assembly. The iron core significantly increases the force output of the motor due to focusing the magnetic field created by the winding. There is a strong attractive force between the iron-core armature and the magnet track, which can be used advantageously as a preload for an air-bearing system. However, these forces can also cause increased bearing wear at the same time. There will also be cogging forces, which can be reduced by skewing the magnets. **Figure 6.8** shows that Slotted from flat.

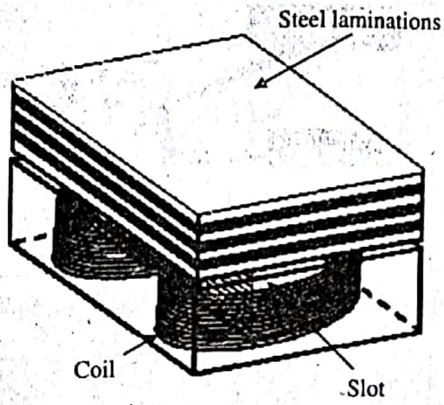


Figure 6.8

Ques 3) What do you mean by linear reluctance motors? Explain construction and working principle of linear reluctance motor.

Ans: Linear Reluctance Motor

An LRM is a linear electric motor, in which, translational force production occurs by the tendency of the moving part to move towards a separate stationary point where the inductance of the excited winding is maximised.

Construction of Linear Reluctance Motor

Figure 6.9 shows the four phase RSRM. The flux path in the longitudinal machine is in the direction of the translator motion. This machine is simpler to manufacture, mechanically robust and has lower eddy current losses, as the flux is in the same direction as the translator movement. The transverse flux design has the flux path perpendicular to the direction of the translator motion. It allows a simple track consisting of individually mounted transverse bars. As the flux is perpendicular to the direction of motion, an electro motive force (EMF) is induced in the core resulting in high eddy current losses (**Figure 6.10**).

There are two distinct configurations of the LRM
1) Longitudinal flux LRM
2) Transverse flux LRM

Both configurations can be obtained by unrolling the stator and rotor of the rotary switched reluctance motor (RSRM) with the radial magnetic flux path and the axial magnetic flux path respectively.

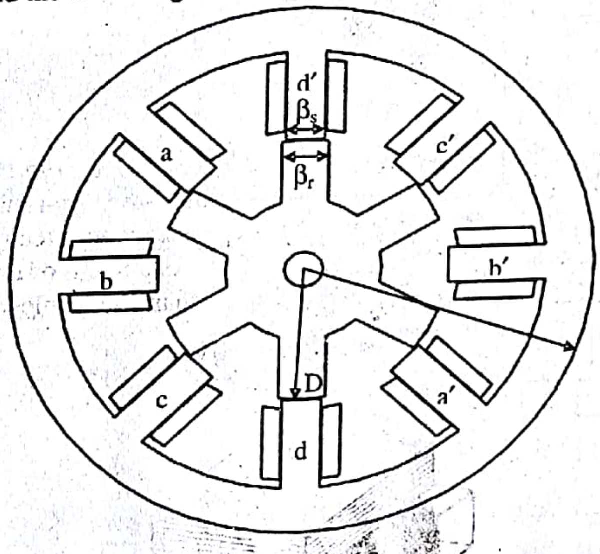
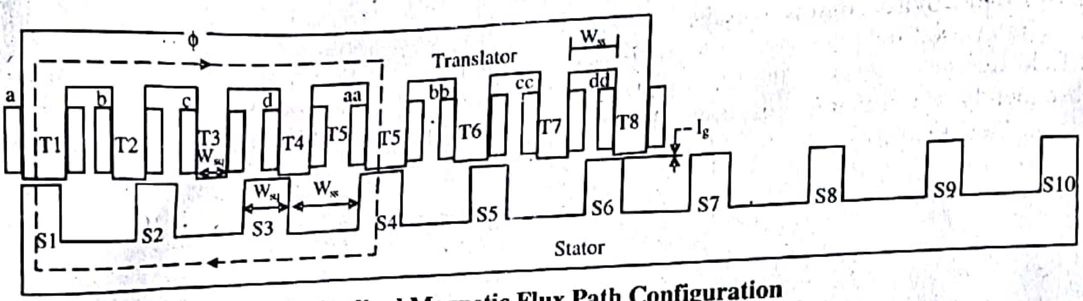


Figure 6.9

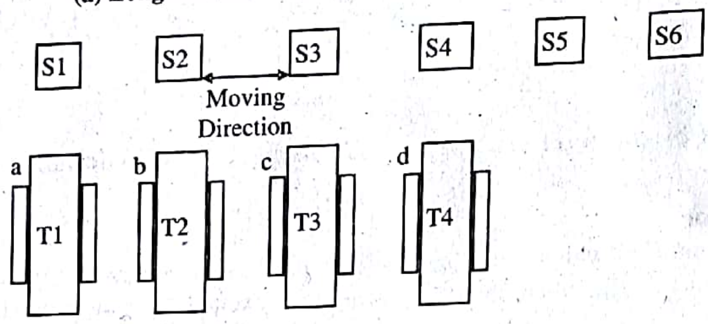
Working Principle of Linear Reluctance Motor

Two topologies of LSRM are Active stator (with windings) Passive stator (without windings) The longitudinal flux and transverse flux configurations for the four-phase LSRM with an active translator and passive stator structure are shown in **Figure 6.10**. The active stator and passive translator LSRM configurations have the advantage in having the power supply and power converters being stationary, resulting in a reduced weight of translator. But, that necessitates a large number of power converter sections along the track resulting in high cost.

On the other hand, the structure with an active translator and passive stator structure requires only one section of the power converter. But the power to the converter in the translator requires transfer by means of contact brushes, which is not desirable for high speed applications.



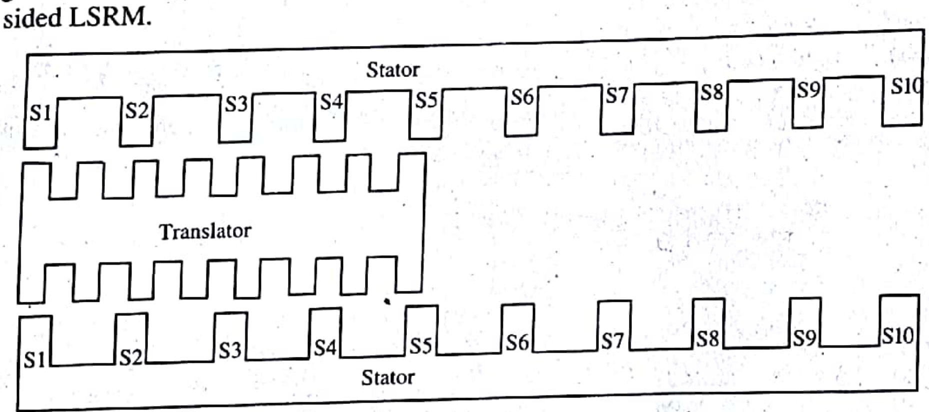
(a) Longitudinal Magnetic Flux Path Configuration



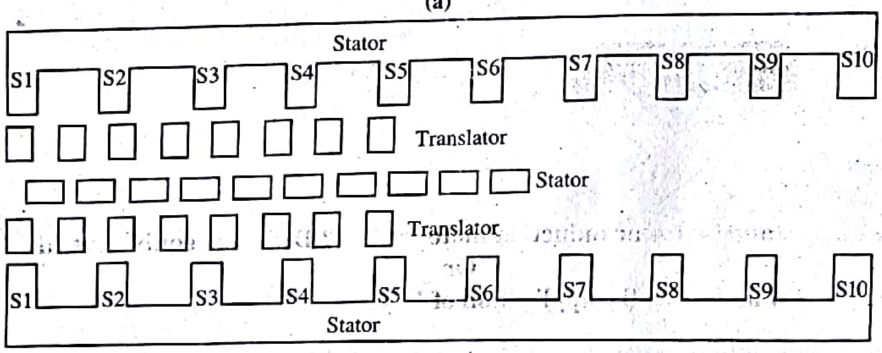
(b) Transverse Magnetic Flux Path Configuration

Figure 6.10

Further, the LSRM may have either two stators or two translators or *vice versa* to make a double-sided LSRM, as shown in **figure 6.11**. It is to be noted that, the double-sided LSRM does not have as much freedom in the air gap tolerance as the single-sided LSRM. The single-sided LSRM provides a net levitation force that can be exploited in maglev systems. But the double-sided LSRM does not produce a net levitation force, and therefore, is unsuitable for such applications. Its advantages are high force density and lower inductance, as it has four air gaps in its flux path, in contrast to the two air gaps in the single sided LSRM.



(a)



(b)

Figure 6.11

Ques 4) Discuss about the construction and working principle of linear synchronous motors.

Ans: Linear Synchronous Motors

A Linear version of a synchronous motor can produce linear or translational motion. **Figure 6.12** shows a schematic diagram of a linear synchronous motor. One member (say the primary) has a three-phase winding, and the other member (say the secondary) has electromagnets, permanent magnets, or superconducting magnets. If the three-phase winding is connected to a three-phase supply, a traveling flux wave will move along the length of the primary.

Construction of Linear Synchronous Motors

The equivalent circuit used for a rotary synchronous motor (**figure 6.12**) can also be used for LSM. If powerful magnets are used, the field due to currents in the three-phase winding is insignificant compared to the field due to the powerful magnets. Consequently, the armature reaction effect can be neglected in an LSM and the synchronous reactance is due primarily to the leakage reactance.

The magnets on the secondary will be synchronously locked with the traveling wave and more at a velocity V_{st}.

$$V_s = 2T_p f$$

Where, T_p is the pole pitch and f is the frequency of the supply. If powerful magnets such as superconducting magnets are used, the LSM can operate at a higher air gap. It can also operate at a leading power factor and better efficiency (because of no-slip loss).

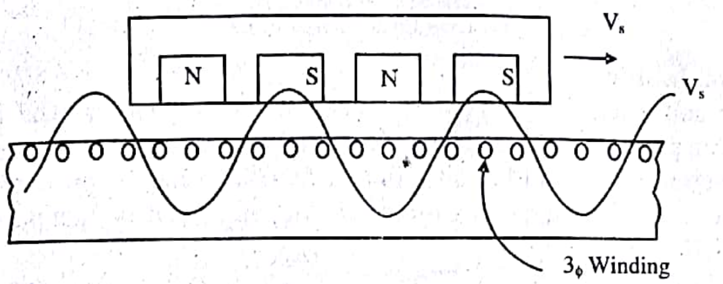


Figure 6.12: Linear Synchronous Motor (LSM)

Working Principle of Linear Synchronous Motors

The working principle is the same as that of the RSM. The equations used to analyze the RSM are also valid in the analysis of the LSM with the following changes: the rotating magnetic field is changed to a travelling magnetic field, torque becomes thrust, rotational synchronous speed becomes linear synchronous speed and the pole pitch, which is the separation between two different polarities of a coil, is added into the equation.

At present, the linear synchronous motor has not been used as widely as the linear induction motor. However, the LSM has great potential in the field of high-speed transportation, where a large air gap clearance is needed. A linear synchronous motor is basically a RSM unrolled flat. The stationary part is called the primary and is equivalent to the RSM stator; the moving part called the secondary and is equivalent to the rotor.

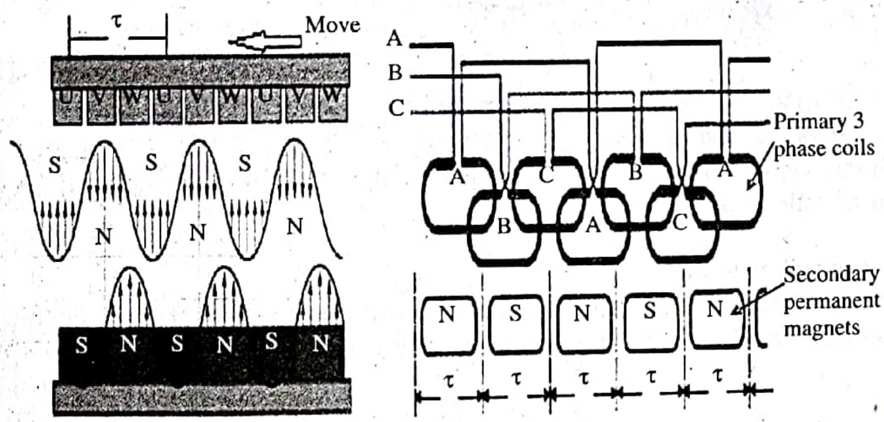


Figure 6.13

Ques 5) What do you understand by linear induction motor (LIM)? Draw the equivalent circuit of LIM.

Or

Discuss the construction of LIM and write the application of LIM.

Ans: Linear Induction Motor (LIM)

A Linear Induction Motor (LIM) is an advanced version of rotary induction motor which gives a linear translational motion instead of the rotational motion. The stator is cut axially and spread out flat. In this type of motor, the stator and rotor are called primary and secondary respectively. The secondary of the linear induction motor consists of a flat aluminium conductor with a ferromagnetic core.

Linear Induction Motor abbreviated as LIM is a special purpose system that we use to achieve rectilinear motion rather than rotational motion as in the case of conventional motors. LIM is quite an engineering marvel, to convert a general motor for a special purpose with more or less similar working principle, thus enhancing its versatility of operation.

Equivalent Circuit of LIM

The equivalent circuit of LIM are shown in **figure 6.14:**

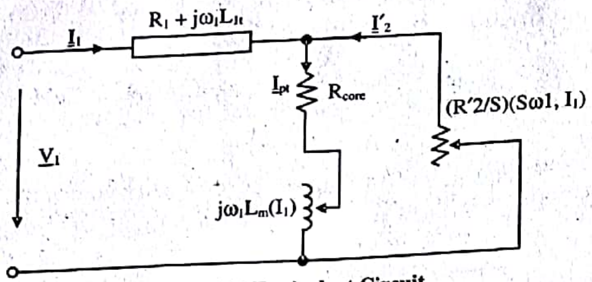


Figure 6.14: LIM Equivalent Circuit

Construction of Linear Induction Motor

Figure 6.15 illustrates the basic constructional diagram of Linear induction motor. The basic construction of a linear induction motor is similar to a three phase induction motor but it does not look alike a conventional induction motor. If we cut the stator of a polyphase induction motor and lay on a flat surface, it forms the primary of the linear induction motor system. Similarly, after cutting the rotor of the induction motor and making it flat, we get the secondary of the system.

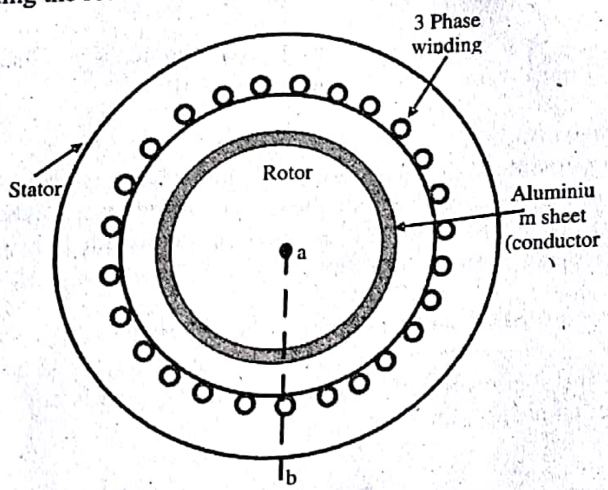


Figure 6.15

There is another variant of LIM also being used for increasing efficiency known as the **Double Sided Linear Induction Motor** or DLIM, as shown in the **figure 6.16**. It has primary on either side of the secondary, for more effective utilisation of the flux from both sides.

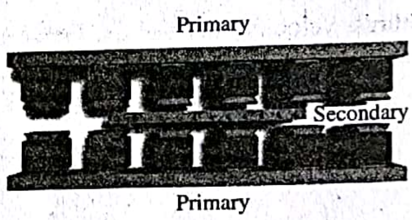


Figure 6.16

Application of Linear Induction Motor

A linear induction motor is not that widespread compared to a conventional motor, taking its economic aspects and versatility of usage into consideration. But there are quite a few instances where the LIM is indeed necessary for some specialised operations.

Few of such applications are listed below:

1) Automatic sliding doors in electric trains.
2) Mechanical handling equipment, such as propulsion of a train of tubs along a certain route.
3) Metallic conveyor belts.
4) Pumping of liquid metal, material handling in cranes, etc.

Ques 5) Explain the working of linear induction motor and derive the expression for linear force. Also draw and discuss the characteristics of LIM.

Ans: Working of a Linear Induction Motor

When the primary of a LIM gets excited by a balanced three-phase power supply, a flux starts traveling along the entire length of the primary. This linearly traveling magnetic field is equivalent to the rotating magnetic field in the stator of a three phase induction motor or a synchronous motor. Electric current gets induced in the conductors of the secondary due to the relative motion between the traveling flux and the conductors. Then the induced current interacts with the traveling flux wave to produce linear force or thrust.

If the primary is fixed and the secondary is free to move, the force will pull the secondary in the direction of the force and will result in the required rectilinear motion. When we give supply to the system the developed field will result in a linear traveling field, the velocity of which is given by the equation,

$$V_s = 2tf_s \text{m/sec}$$

Where f_s is the supply frequency in Hz, V_s is the velocity of the linear traveling field in meter per second, and t is linear pole pitch, i.e., pole to pole linear distance in meter.

For the same reason as in the case of an induction motor, the secondary or runner cannot catch the speed of the magnetic field. Hence there will be a slip. For a slip of s, the speed of the linear induction motor will be,

$$V = (1 - s)V_s$$

Expression of the Linear Force of LIM

The linear synchronous speed of the travelling wave is given by the equation shown below;

$$v_s = 2f(\text{pole pitch})\frac{m}{s}, \quad \text{..... (1)}$$

Where, f is the supply frequency in hertz.

In the rotary induction motor, the speed of the secondary in the linear induction motor is less than the synchronous speed v_s and is given as,

$$v_r = v_s(1 - s) \quad \text{..... (2)}$$

Where s is the slip of the linear induction motor and is given as,

$$s = \frac{v_s - v_r}{v_s} \text{pu} \quad \text{..... (3)}$$

The linear force is given by the equation shown below.

$$F = \frac{\text{air gap power}}{\text{linear synchronous velocity}(v_s)}$$

The thrust velocity curve of the linear induction motor is similar to that of the speed torque curve of the rotary induction motor. It is shown in the **figure 6.17.**

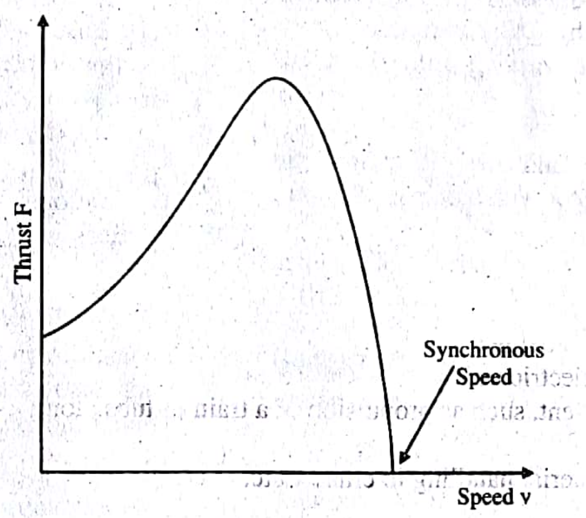


Figure 6.17

If a rotary induction motor is compared with the linear induction motor, the LIM requires a larger air gap and hence, the magnetising current is greater and the power factor and efficiency of the motor are lower. In the rotary induction motor the stator and the rotor area are same whereas in the LIM the one of the two is shorter than the other. At the steady speed, the shorter part will be passing continuously over a new part of the other member.

MODEL PAPER

SPECIAL ELECTRICAL MACHINE

B. TECH. EIGHTH SEMESTER EXAMINATION

Time: 3 Hours **Max. Marks: 100**

Note: The question paper shall have four parts.

PART- A

Attempt all questions. (5 marks each)

1) Describe the various types of servomotor and also write the applications of servomotor. (05)

2) Explain the performance characteristics of AC servomotor with suitable diagram. (05)

3) Discuss about the Armature controlled DC servomotors also discuss its operation with suitable diagram. Also sketch its characteristics graph. (05)

4) Explain the construction and theory of operation of Hybrid type stepper motor. (05)

5) Explain construction and principle of working of single phase AC series motor. (05)

6) What do you mean by Reluctance Motor? Explain principle operation of Reluctance motor. (05)

7) Explain types of brushless DC motor. (05)

8) Explain the working of linear induction motor and derive the expression for linear force. Also draw and discuss the characteristics of LIM. (05)

PART- B

Answer any 2 question out of 3 questions (10marks each).

9) What do you understand by DC servomotor? Also explain the construction and working principle of DC servomotor. (10)

Or

Explain AC servomotor and also explain the construction of AC servomotor with suitable diagram.

10) Explain the various modes of excitation of stepper motor driving. (10)

Or

What do you mean by Stepper Motor? Explain construction and working principle of stepper motor. Write the different types of stepper motor.

11) What is Hysteresis motor? Explain constructional detail of Hysteresis motor with suitable diagram. (10)

Or

Define torque equation and torque-slip characteristics of Reluctance motor. Write application of reluctance motor.

PART- C

Answer any 2 question out of 3 questions (10 marks each).

12) Describe all types of linear motor. (10)

Or

Write a short note with proper diagram on:

i) Bifilar windings

ii) Monofilar windings

13) What do you mean by linear reluctance motors? Explain construction and working principle of linear reluctance motor. (10)

Or

Explain static and dynamic characteristics of stepper motor with suitable diagram and discuss an example.

14) Write a short note on: (10)

i) Permanent Magnet armature controlled DC servomotor

ii) Series Split Field DC Servomotor

Or

How can a universal motor operate on either DC or AC supply?

PART- D

Answer any 2 question out of 3 questions (10 marks each).

15) Explain the characteristics of single phase AC series motor. Write the applications of it. (10)

Or

i) Discuss about the construction and working principle of linear synchronous motors.

ii) Write the advantages disadvantages and application of stepper motor.

16) i) Explain the drive circuits of stepper motor. Also give the comparison between them. (10)

ii) Write short note on AC drag cup servomotor.

Or

What do you mean by linear motor? Explain construction and principle of working of linear motor and also write the advantages and disadvantages of linear motor.

17) Write the selection criteria of stepper motor. Also write the application of stepper motor. (10)

Or

Explain the variable reluctance stepper motor and explain the theory of operation with suitable diagram. Also write its type.