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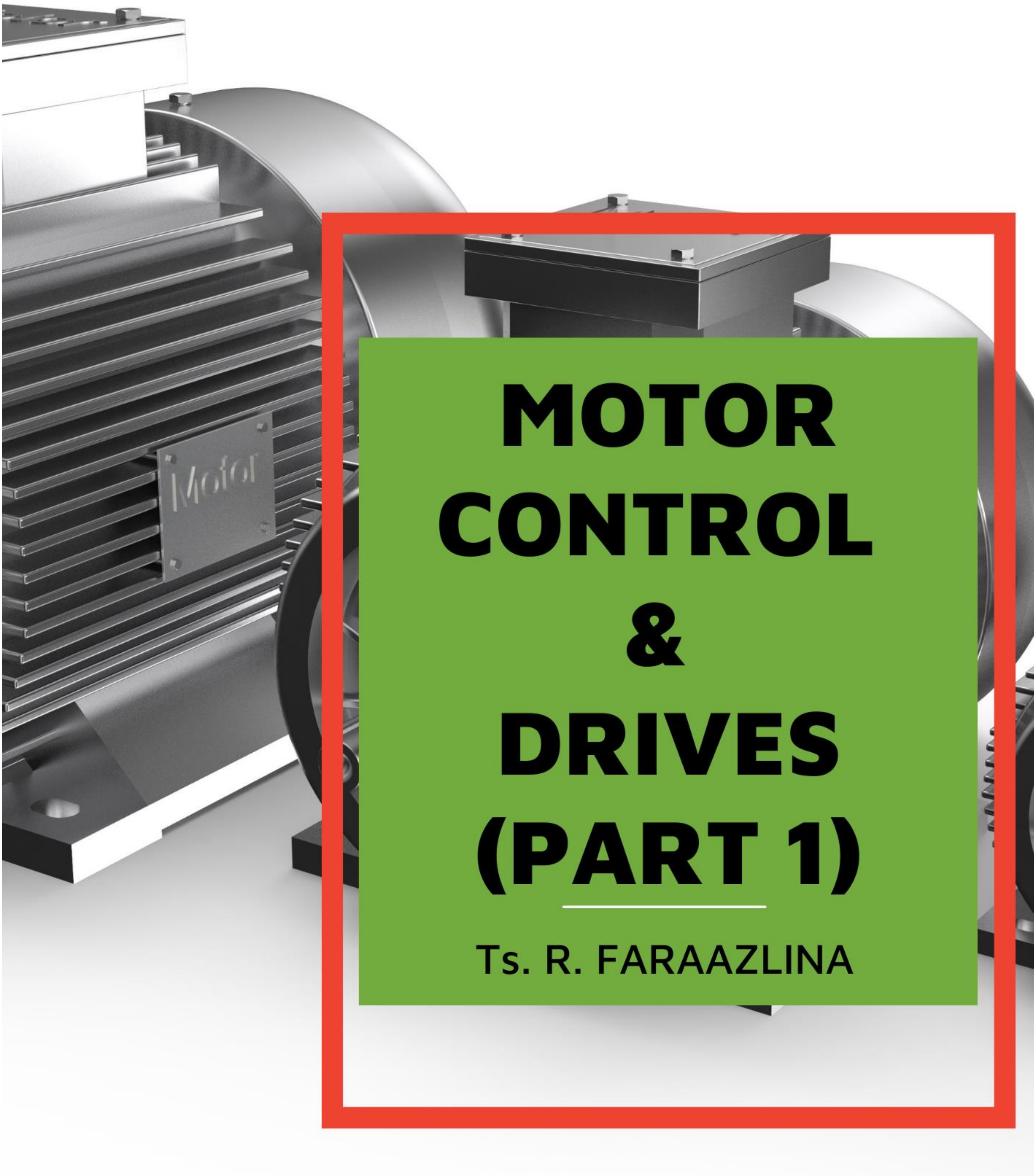


# MOTOR CONTROL & DRIVES (PART 1)

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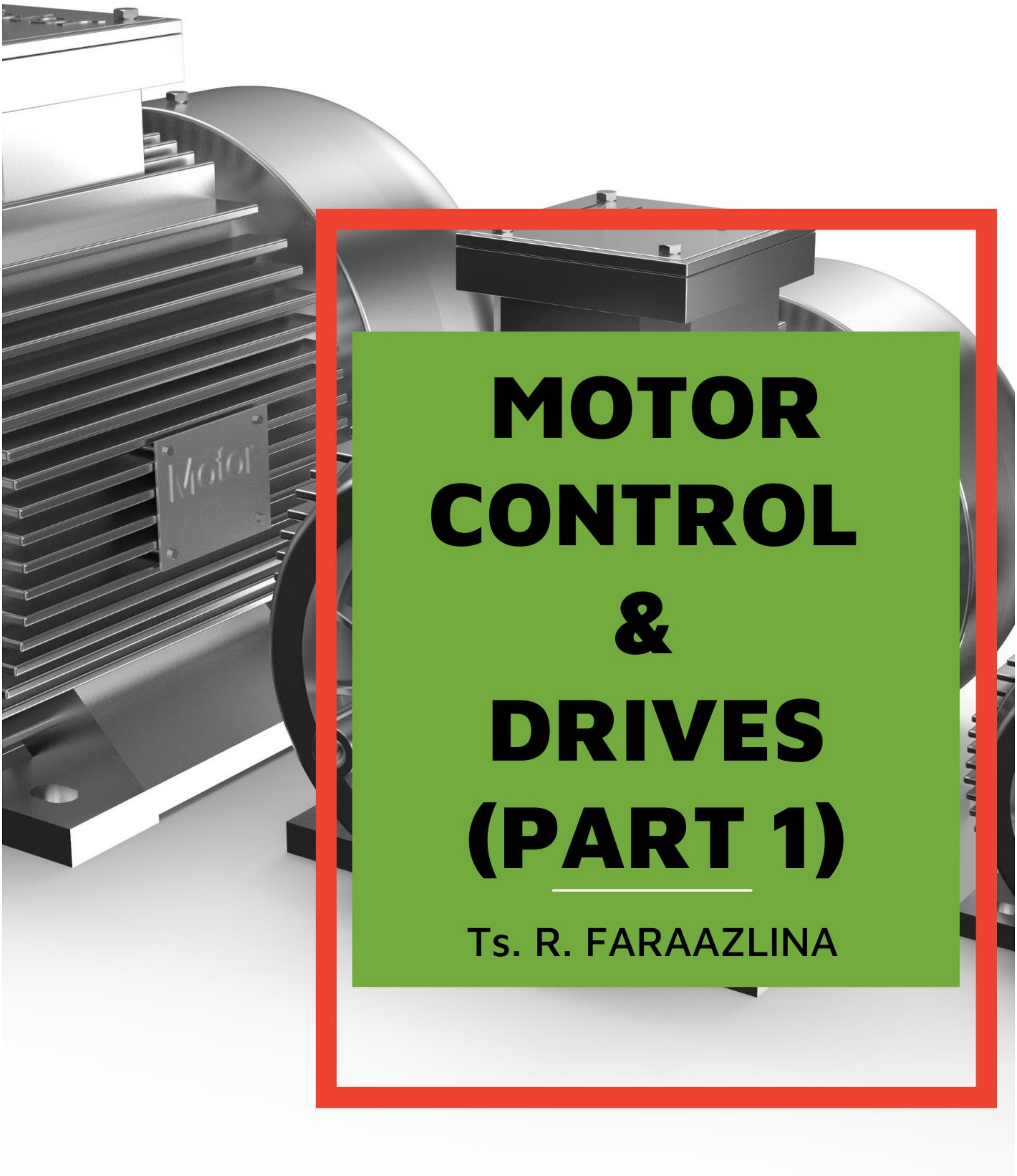


# MOTOR CONTROL & DRIVES (PART 1)

Ts. R. FARAAZLINA

# PREFACE

This book book was written with the specific aim of providing the necessary principles of motor control & drives to the students and it's covering the syllabus of the Diploma program according to the Polytechnics curriculum. the relevant theories are arranged to introduce the topics in a clear and simple way to enhance student's understanding.

The book presents the basic theories of motor control & drives in a straightforward manner, supported with diagrams and solved examples with review questions and calculation questions for all topics.

Chapter 1 emphasizes the fundamentals of electrical motor. Chapter 2 focus on introduction of electrical drives, discussing the definition, application, and four-quadrant principles of electrical motor. Chapter 3 discusses the speed control of DC motor. this chapter includes the method for controlling the speed and complete with calculation examples by using each method. Chapter 4 discusses the speed control of AC motor focusing on induction motor.

It is sincerely hoped that this book will be most welcomed by the lecturers and will be useful to the students of polytechnics. any constructive comments and suggestions from the readers are highly appreciated.

Thank you and all the best.

*Ts. R. Faraazlina*

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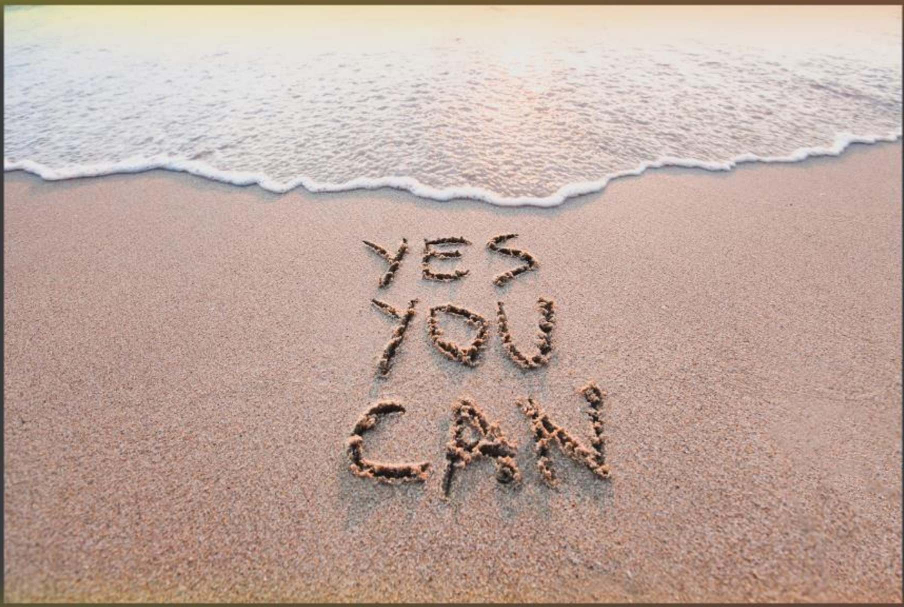



# Push yourself because no one else is going to do it for you.

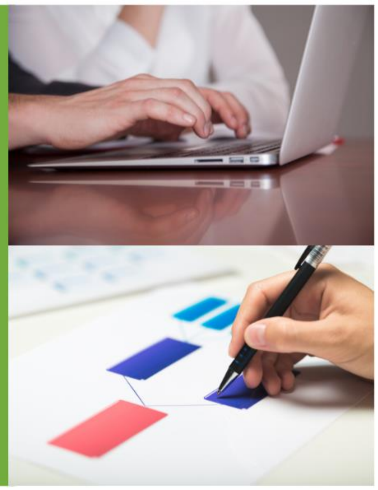
MOTIVATION QUOTES

Theory of Electrical Source, Motor or Machine

Torque, Horsepower, Speed

Fundamental of Electrical Drives

Connection of Electrical Motor



# 01

# BASIC FUNDAMENTALS OF ELECTRICAL MOTOR

# BASIC FUNDAMENTAL OF ELECTRICAL MOTOR

## 1.1 TYPES OF ELECTRICAL SUPPLY

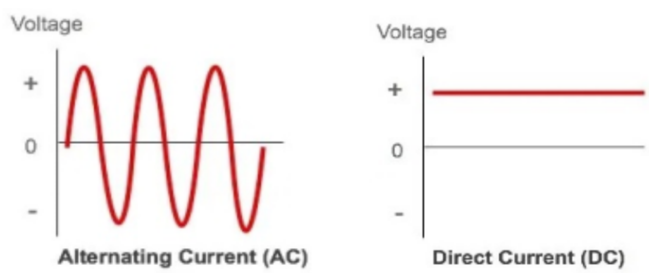



Figure 1.1: Types of Electrical Supply

**AC**

- Rotating magnet along wire
- Safe to transfer over long distance - provide more power.
- Switching direction forward / backward
- Frequency: 50 - 60Hz
- Current of magnitude varying with time
- Obtains from AC generator
- Power factor: 0 - 1 (Usually 0.85 - 9)

**DC**

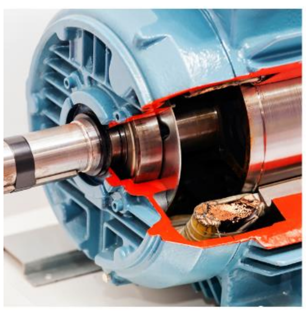
- Steady magnetism along the wire.
- Voltage of DC cannot travel very far until it begins to lose energy.
- It flows in one direction in the circuit.
- The frequency of direct current is zero.
- Electrons move steadily in one direction or 'forward'.
- Obtains from cell or battery
- Power factor is always 1

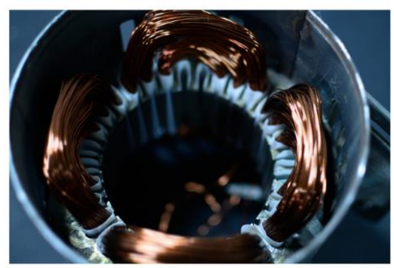
# BASIC FUNDAMENTAL OF ELECTRICAL MOTOR

## 1.2 TYPES OF ELECTRICAL MOTOR

AC MOTOR

- Commutator Motor (Single Phase Series, Repulsion, Schrage).
- Synchronous Motor
- Induction Motor (Brushless, Carbon Brush - Single Phase & Three Phase.





DC MOTOR

- Separately Excited Motor
- Series Motor
- Shunt Motor
- Compound Motor
- Permanent Magnet Motor

# BASIC FUNDAMENTAL OF ELECTRICAL MOTOR

## 1.3 TYPES OF ELECTRICAL DRIVES

- A drive is an electrical or electronic device used to control the speed and motion of electrical machines such as motors and robots etc.
- The device used for motor speed control is known is an electrical drive.
- They are constant and variable speed controller and widely used in industrial automation.
- There are two types of drive: AC Drives and DC Drives.
- AC and DC Drives offer robust performance and minimal maintenance for various applications.

**AC DRIVES**

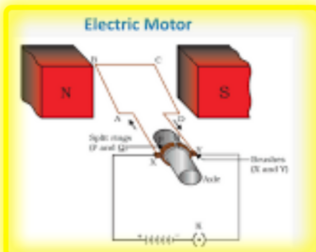
- Less Maintenance
- Power circuit and control - difficult & complex
- Use for AC motor - use converter and inverter
- Large
- Brake & accelerating when changing the frequency of the supply

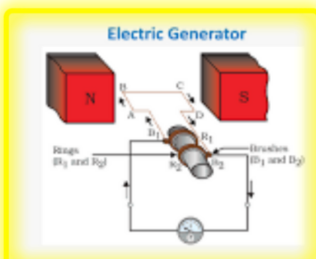
**DC DRIVES**

- More Maintenance
- Power circuit & control - easy & simple
- Use for DC Motor - have chopping circuit & only converter
- Small - Power & weight
- Braking/Brake when applying resistance at motor.

# BASIC FUNDAMENTAL OF ELECTRICAL MOTOR

## 1.4 COMPARISON BETWEEN MOTOR AND GENERATOR




- An electric motor is an electrical machine that converts electrical energy into mechanical energy.
- Most electric motors operate through the interaction between the motor's magnetic field and electric current in a wire winding to generate force in the form of torque applied on the motor's shaft.
- Electric motors can be powered by direct current (DC) sources, such as from batteries, or rectifiers, or by alternating current (AC) sources, such as a power grid, inverters or electrical generators.
- While, an electrical generator is mechanically identical to an electric motor, but operates with a reversed flow of power, converting mechanical energy into electrical energy.

**MOTOR**

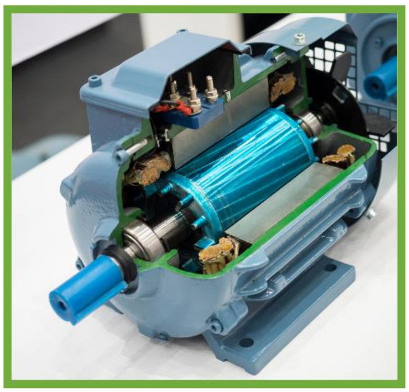
- Uses electricity
- Driven element: Shaft of the motor is driven by the magnetic force developed by armature and field.

**GENERATOR**

- Generates electricity
- Driven element: Shaft is attached to the rotor and is driven by mechanical force.

# BASIC FUNDAMENTAL OF ELECTRICAL MOTOR

## 1.5 TORQUE, SPEED AND HORSEPOWER



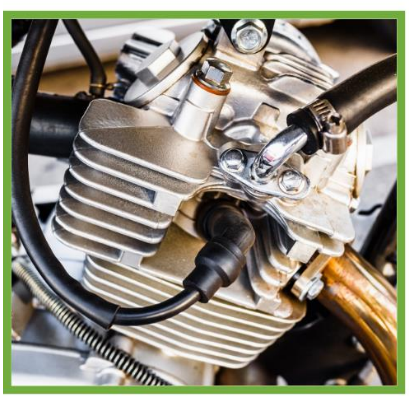
- **Speed, Ns** – How fast? → rpm
- **Torque, T** – T=F x r (Work & Force) = Force x Distance → Nm
- **Horse Power, HP** – Accelerate. How quickly accomplish the work
  – 1HP = 746W (Power) = Torque x Speed

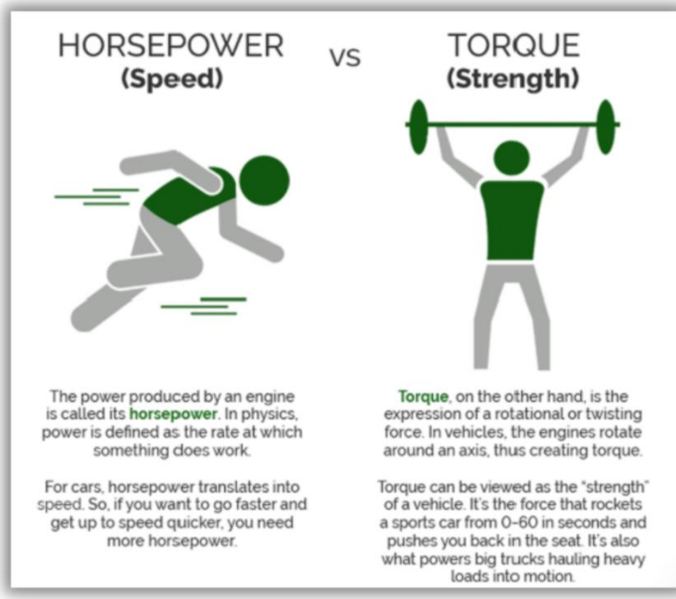
$$T = \frac{HP \times 5252}{rpm}$$

$$T(Constant) = \frac{HP\uparrow \times 5252}{rpm\uparrow}$$ → Production increase

$$Ns(Speed\ Constant) = \frac{HP\uparrow \times 5252}{T\uparrow}$$ → Production increase

$$HP(Constant) = \frac{rpm\ \uparrow \times T\downarrow}{5252}$$

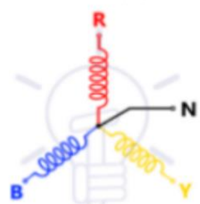




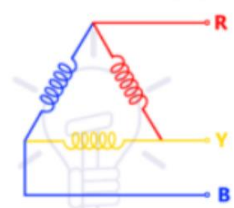
# BASIC FUNDAMENTAL OF ELECTRICAL MOTOR

## 1.6 COMPARISON BETWEEN STAR AND DELTA CONNECTION IN MOTOR

Star (Y)




Delta (Δ)




### Star

- Each point same voltage (Vp=230V).
- Run 1/3 of motor rated for torque and power.
- Line voltage is root three times phase voltage ($V_L=\sqrt{3}xV_P$). So, $V_L \neq V_P$.
- Have two different voltages system. For example, in a 230V/400V system, the voltage between any of the phase wire and neutral wire is 230V and the voltage between any two phases is 400V.
- Line current and Phase current are same ($I_L=I_P$).
- Total three phase Power : $P = 3 \times V_P \times I_P \cos(\phi)$ or $P = \sqrt{3} \times V_L \times I_L \cos\phi$).
- Often used is application which require less starting current.

### Delta

- Each point receives line voltage ($V_L$=415V).
- Run/Operate in full torque and power.
- Line voltage is equal to phase voltage, $V_L=V_P$.
- Only a single voltage magnitude.
- Line current is root three times the phase current ($I_L=\sqrt{3}xI_P$). So, $I_L \neq I_P$.
- Total three phase Power : $P = 3 \times V_P \times I_P \cos(\phi)$ or $P = \sqrt{3} \times V_L \times I_L \cos\phi$).
- Often used is applications which require high starting torque.

**STAR**

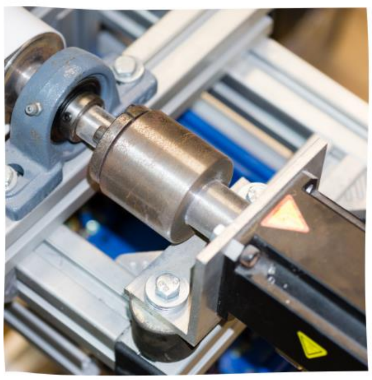
$$A=\frac{PQ}{R}+Q+P \quad B=\frac{RP}{Q}+P+R \quad C=\frac{QR}{P}+Q+R$$

**DELTA**

$$P=\frac{AB}{A+B+C} \quad Q=\frac{AC}{A+B+C} \quad R=\frac{BC}{A+B+C}$$

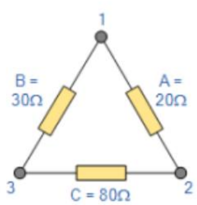
# BASIC FUNDAMENTAL OF ELECTRICAL MOTOR

## 1.6 COMPARISON BETWEEN STAR AND DELTA CONNECTION IN MOTOR



**Example:**

Convert the following Delta Resistive Network into an equivalent Star Network.



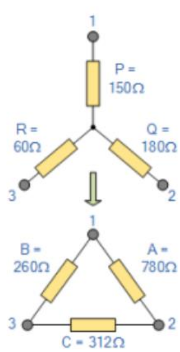

$$Q = \frac{AC}{A+B+C} = \frac{20\times 80}{130} = 12.31\Omega$$

$$P = \frac{AB}{A+B+C} = \frac{20\times 30}{130} = 4.61\Omega$$

$$R = \frac{BC}{A+B+C} = \frac{30\times 80}{130} = 18.46\Omega$$

**Example:**

Convert the following Delta Resistive Network into an equivalent Delta Network.




$$A = \frac{QP}{R} + Q + P = \frac{180\times 150}{60} + 180 + 150 = 780\Omega$$

$$B = \frac{RP}{Q} + R + P = \frac{60\times 150}{180} + 60 + 150 = 260\Omega$$

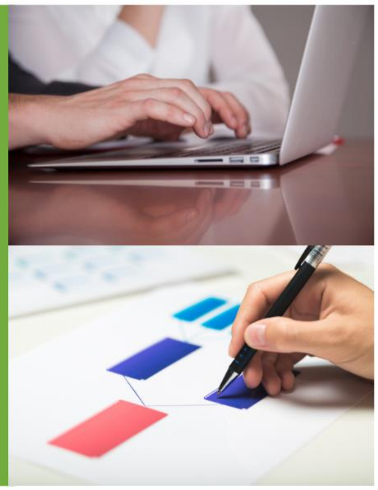
$$C = \frac{QR}{P} + Q + R = \frac{180\times 60}{150} + 180 + 60 = 312\Omega$$


# It's going to be HARD, but HARD does not mean IMPOSSIBLE

## MOTIVATION QUOTES

Describe about an electrical drive system, understand and analyze the concept of four quadrants in motor operations.

study the function & application of elecrical drives in motor system generally.



# 02

# INTRODUCTION TO ELECTRICAL DRIVES

# INTRODUCTION TO ELECTRICAL DRIVES

## 2.1 ELECTRICAL DRIVE

- Systems employed for motion control are called drives. Motion control is required in industrial as well as domestic applications like transportation system, rolling mills, paper mills, textile mills, machine tools, fans, pumps, robots, washing machines etc.
- A drive system is basically having a mechanical load, a transmission system and a prime mover (electric motor).
- Electric motor drives control the direction, speed, torque and other operating function of an electric motor in addition to providing motor protection and monitoring functions.
- Speed of an electrical machine (motor or generator) can be controlled by the source current's frequency as well as the applied voltage.
- **Important:** An electric drive is a system consisting of one or several electric motors and of the entire electric control equipment designed to govern the performance of these motors. (IEEE Standard Dictionary of Electrical and Electronics Terms).
- An electrical driver can be defined as an electromechanical device for converting electrical energy into mechanical energy to impart motion to different machines and mechanisms for various kinds of process control. Its functions are to turn and drive the motor according to load requirements with respect to the desired torque or speed needed by the user.

**Rolling Mills** **Paper Mills** **Pump**

*Figure 2.1: Application of Electrical Drive System*

# INTRODUCTION TO ELECTRICAL DRIVES

## 2.2 ADVANTAGES

- They have flexible control characteristics. The steady state and dynamic characteristics of electric drives can be shaped to satisfy the load requirements.
- Drives can be provided with automatic fault detection systems. Programmable logic controller and computers can be employed to automatically control the drive operations in a desired sequence.
- They are available in wide range of torque, speed and power (both ac and dc motor)
- They are adaptable to almost any operating conditions such as explosive and radioactive environments
- Capable operate in all the four quadrants of speed-torque plane
- They can be started instantly and can immediately be fully loaded
- Control gear requirement for speed control, starting and braking is usually simple and easy to operate.
- No exhaust gases emitted
- Works to almost any type of environmental conditions

**Conveyor** **Chiller** **Lifts**

*Figure 2.2: Application of Electrical Drive System*

# INTRODUCTION TO ELECTRICAL DRIVES

## 2.3 BLOCK DIAGRAM

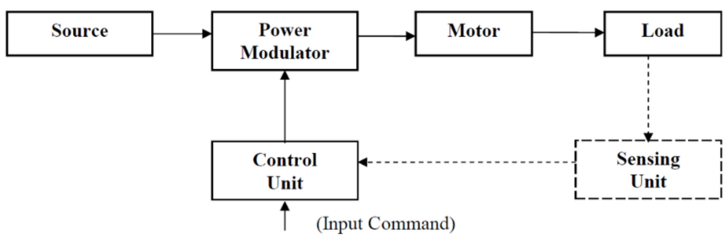



***Figure 2.3: Block Diagram of Electrical Drive System***

A modern variable speed electrical drive system has the following components

1.Source
2.Power Modulator
3.Electrical machines(motor) and loads
4.Control unit5.Sensing unit

1.Electrical Sources

- The power source provides the energy to the drive system. It may be dc or ac (single-phase or three-phase).
- Very low power drives are generally fed from single phase sources. Rest of the drives is powered from a 3 phase source. Low and medium power motors are fed from a 200V to 400V supply. For higher ratings, motors may be rated at 3.3KV, 6.6KV and 11 KV. Some drives are powered from battery.

# INTRODUCTION TO ELECTRICAL DRIVES

2.Power Modulators/Converter

- The converter interfaces the motor with the power source and provides the motor with adjustable voltage, current and frequency. During transient period such as starting, braking and speed reversal, it restricts source and motor current within permissible limits. Also the converter converts the electric waveform into required signal that requires the motor.

Functions:

- Modulates flow of power from the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load.
- During transient operation, such as starting, braking and speed reversal, it restricts source and motor currents with in permissible limits.
- It converts electrical energy of the source in the form of suitable to the motor
- Selects the mode of operation of the motor (i.e.) Motoring and Braking.

# INTRODUCTION TO ELECTRICAL DRIVES

Types of Power Modulators

In the electric drive system, the power modulators can be any one of the following

- Cycloconverters (Frequency conversion)
- AC voltage controllers (AC to AC converters)



- Controlled rectifiers (AC to DC converter)


- Inverters (DC to AC converter)


- DC Choppers (DC to DC converter)

# INTRODUCTION TO ELECTRICAL DRIVES

3.Sensing Unit

- Speed Sensing
- Torque Sensing
- Position Sensing
- Current sensing and Voltage Sensing from Lines or from motor terminals from Load
- Temperature Sensing

Functions:

- Modulates flow of power from the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load.
- During transient operation, such as starting, braking and speed reversal, it restricts source and motor currents with in permissible limits.
- It converts electrical energy of the source in the form of suitable to the motor
- Selects the mode of operation of the motor (i.e.) Motoring and Braking.

# INTRODUCTION TO ELECTRICAL DRIVES

4. Electrical Machines

Most commonly used electrical machines for speed control applications are the following:

i. DC Machines

- Shunt, series, compound, separately excited DC motors and switched reluctance machines.

ii. AC Machines

- Induction, wound rotor, synchronous, PM synchronous and synchronous reluctance machines.

iii. Special Machines

- Brush less DC motors, stepper motors, switched reluctance motors are used.
- The mechanical load usually called as machinery such as flow rates in pump, fans, robots, machine tools, trains and drills are coupled with motor shaft.

**Stepper motor**

**Switch Reluctance Motor**

***Figure 2.4: Example of Special Machines***

# INTRODUCTION TO ELECTRICAL DRIVES

5. Control Unit/Controller

Control unit for a power modulator are provided in the control unit. It matches the motor and power converter to meet the load requirements.

**Speed-Torque Characteristic**

i. DC Motor

- At constant V/f, if the speed is varied up to the base speed of the motor, the power will vary according to P=2πNT. The motor operates in variable power or constant torque mode.
- For a speed up to the base speed, the armature voltage is varied and the torque is maintained constant.
- Once the rated armature voltage is applied, the speed-torque relationship follows the natural characteristic of the motor and the power (= torque X speed) remains constant.
- As the torque demand is reduced, the speed increases.
- At a very light load, the speed could be very high and it is not advisable to run a dc series motor without a load.

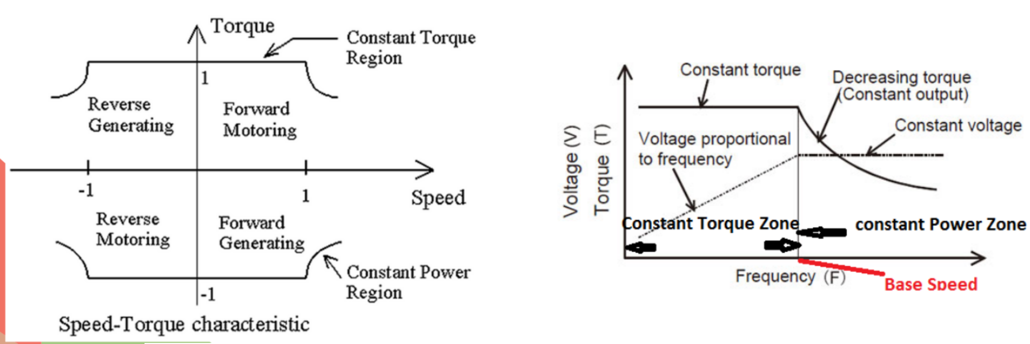



***Figure 2.5: Speed-Torque Characteristics of DC Motor***

# INTRODUCTION TO ELECTRICAL DRIVES

### ii. Speed-Torque characteristic for AC motor

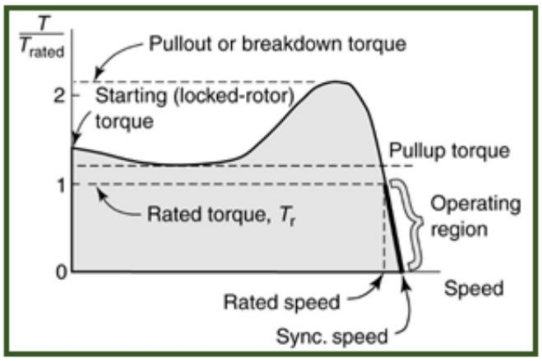



*Figure 2.6: Speed-Torque Characteristics of AC Motor*

### i. **Locked Rotor Torque** or **Starting Torque**

The **Locked Rotor Torque** or **Starting Torque** is the torque develop of the electrical motor when its starts at rest or zero speed.

- A high Starting Torque is more important for application or machines hard to start - as positive displacement pumps, cranes etc. A lower Starting Torque can be accepted for centrifugal fans or pumps where the start load is low or close to zero.
- Locked rotor torque is usually stands at 1.5 T of the full load of the motor.
- It needs a high torque to start and rotate the motor from a standstill condition to a rotating condition.
- As high torque is obtained, starting current is generated to develop the high starting torque.

# INTRODUCTION TO ELECTRICAL DRIVES

ii.Pull-up Torque

- The Pull-up Torque is the minimum torque developed by the electrical motor when it runs from zero to full-load speed (before it reaches the break-down torque point)
- When the motor starts and begins to accelerate the torque in general decrease until it reach a low point at a certain speed - the pull-up torque - before the torque increases until it reach the highest torque at a higher speed - the break-down torque - point.
- The pull-up torque may be critical for applications that needs power to go through some temporary barriers achieving the working conditions.

iii.Break-down Torque

- The Break-down Torque is the highest torque available before the torque decreases when the machine continues to accelerate to the working conditions.

# INTRODUCTION TO ELECTRICAL DRIVES

## 2.4 FOUR QUADRANTS IN MOTOR OPERATIONS

For multi quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed.
A motor operates in two modes – Motoring and braking.

- In motoring, it converts electrical energy into mechanical energy, which supports its motion.
- In braking, it works as a generator converting mechanical energy into electrical energy and thus opposes the motion.
- Motor can provide motoring and braking operations for both forward and reverse directions.

Figure 1.8 shows the torque and speed co-ordinates for both forward and reverse motions. Power developed by a motor is given by the product of speed and torque. For motoring operations power developed is positive and for braking operations power developed is negative.

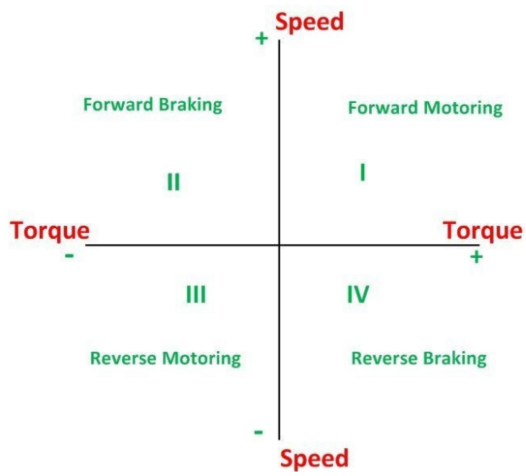



***Figure 2.6: Four-Quadrants in Motor Operation***

# INTRODUCTION TO ELECTRICAL DRIVES

## 2.4 FOUR QUADRANTS IN MOTOR OPERATIONS

| | |
|---|---|
| **Quadrant 1**<br>Forward Motoring | • Motor condition where the motor has positive torque and speed.<br>• Motor will receive electric supply from source and convert it into mechanical energy to rotate the mechanical load.<br>• Rotation produced is clockwise.<br>• Energy convert from electrical form to mechanical form |
| **Quadrant 2**<br>Forward Braking | • Motor operates at positive speed in and negative torque.<br>• During the operation, it can act as braking or generation<br>• Rotation produced is clockwise.<br>• Torque produced by the motor used to brake the forward rotating of the motor |
| **Quadrant 3**<br>Reverse Motoring | • Operating principle is similar to quadrant 1, the difference is the direction of rotor rotation of is opposite to both this quarter.<br>• The torque and speed are negative.<br>• Motor movements produced are anti-clockwise. |
| **Quadrant 4**<br>Reverse Braking | • Motor condition where the motor has negative torque and positive speed.<br>• Motor will receive electric supply from source and convert it into mechanical energy to rotate the mechanical load.<br>• Rotation produced is counter clockwise/anti clockwise. |

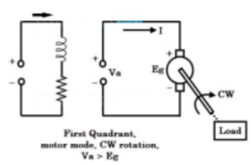
# INTRODUCTION TO ELECTRICAL DRIVES

## 2.5 CIRCUIT DIAGRAM OF FOUR QUADRANTS

**Quadrant 1**

In this mode of operation, the applied voltage is positive and greater than the back emf of the motor and therefore a positive current flow into the motor. Motor will receive electric supply from source and convert it into mechanical energy to rotate the mechanical load. Since both current and voltage are positive, the power becomes positive. And also the speed and torque are also positive in this quadrant. Therefore, the motor rotates in forward direction.

Forward Motoring



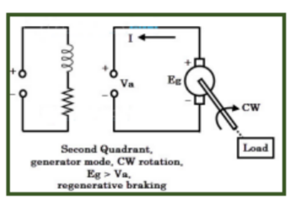

First Quadrant, motor mode, CW rotation, Va > Eg

**Quadrant 2**

In this mode of operation, the motor runs in forward direction and the induced emf continues to be positive. But the supplied voltage is suddenly reduced to a value which is less than the back emf. Hence the current (there by torque) will reverse direction. This negative torque reverses the direction of energy flow.

Since the load torque and motor torque are in opposite direction, the combined effect will cause to reduce the speed of the motor and hence back emf (motor emf is directly proportional to the speed) falls again below the applied voltage value. Both current and voltage become positive and the motor settle down to first quadrant again. The process by which the mechanical energy of the motor is returned to the supply is called as regenerative braking.

Forward Braking




Second Quadrant, generator mode, CW rotation, Eg > Va, regenerative braking

# INTRODUCTION TO ELECTRICAL DRIVES

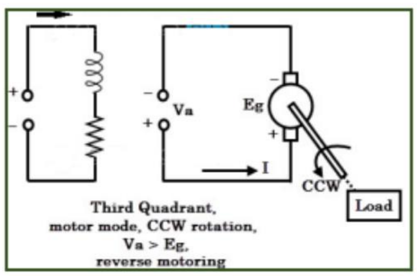
## 2.5 CIRCUIT DIAGRAM OF FOUR QUADRANTS

**Quadrant 3**

This is the third quadrant operation of the motor in which both motor voltage and current are negative. Thus the power is positive, i.e., the power is supplied from source to load. Due to the reverse polarity of the supply, the motor starts rotating in a counterclockwise direction (or reverse to normal operation). The torque and speed are negative.

The operation of this quadrant is similar to the first quadrant, but only difference is the direction of rotation. The magnitude of voltage to the motor decides the appropriate speed in reverse direction Motor movements produced are counterclockwise.

Reverse Motoring




Third Quadrant, motor mode, CCW rotation, $V_a > E_g$, reverse motoring

# INTRODUCTION TO ELECTRICAL DRIVES

## 2.5 CIRCUIT DIAGRAM OF FOUR QUADRANTS

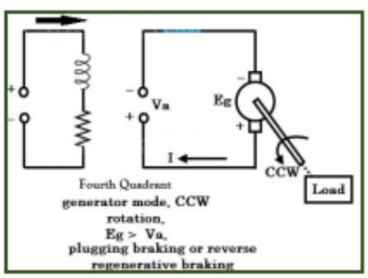
**Quadrant 4**

This is the quadrant-4 mode of operation in which motor voltage is still negative and its armature current is positive. This mode of operation is similar to the second quadrant operation and once again the regeneration occurs whenever the back emf is more than the negative supply voltage.

Hence the torque will be positive which opposes the load torque, thus the speed of the motor will be reduced during reverse operation of the motor. 'This mode of operation is mostly used for plugging in order to stop the motor rapidly. During plugging, the armature terminals are suddenly reversed, which causes the back emf to force an armature current to flow in reverse direction.

Now the effective voltage across the motor becomes 2V (as V+ Eb). A braking resistor in series with the motor has to be connected to limit this current. Braking by plugging gives greater torque and more rapid stop, but the current drawn from the supply and energy stored in mechanical parts must be dissipated in resistance.

Reverse Braking



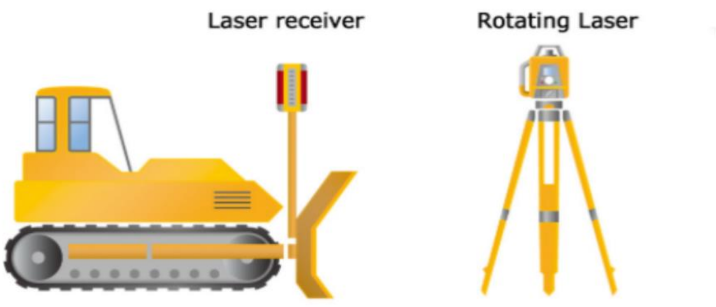
# INTRODUCTION TO ELECTRICAL DRIVES

## 2.6 APPLICATION OF FOUR QUADRANT

- Electric traction system
- Battery operated vehicles
- Lifts and cranes
- Engine test loading systems
- Spindle and tool drives in machine tools
- Auxiliary drives in robotic systems
- Position control systems

**Electric traction system**

**Battery operated vehicles**




**Position control systems – Relative Height Control**

***Figure 2.7: Application of Four-Quadrant***

# INTRODUCTION TO ELECTRICAL DRIVES

## 2.7 REVIEW QUESTION

1. Define an electrical drive in motor control
2. State THREE (3) advantages of electric drives
3. Explain the operation of DC motor in the four quadrants of the torque-speed plane
4. Sketch and label the operation of DC motor in the four quadrants of the torque-speed plane
5. Draw the block diagram of an electrical drive
6. Differentiate the characteristics of DC and AC drivers

## 2.8 CALCULATION QUESTION

1.A standard 3-phase, 10Hp, 575V, 1750 r/min, 60 Hz NEMA class D squirrel-cage induction motor develops a torque of 110N-m at a speed of 1440r/min. if the motor is excited at a frequency of 25Hz, calculate the following:

a) The required voltage to maintain the same flux in the machine
b) The new speed at a torque of 110N-m

2. A 240V, 10hp, 4-pole, 50Hz, Y-connected induction machine has a full load of 5%.

a) What is the synchronous speed of this motor?
b) What is the rotor speed of this motor?
c) What is the rotor frequency of this motor at the rated load?
d) What is the shaft torque of this motor at the rated load?

# INTRODUCTION TO ELECTRICAL DRIVES

## 2.8 CALCULATION QUESTION

3. A three phase, 6 poles squirrel cage induction motor is rated 460V, 60 Hz produce 100Nm at 950 rpm. Calculate the required voltage and frequency to be applied to the stator if the motor run at 2250 rpm and produce 100Nm.

4. A three phase, 4 poles squirrel cage induction motor is rated 575V, 50 Hz produce 110Nm at rotational speed 1440 rpm. If the motor is set to new frequency at 25Hz, calculate the new speed at 25Hz.

5. A three phase, squirrel cage induction motor operates at 500V, 60 Hz produce 120Nm at 1650 rpm. Given that the synchronous speed is 1800 rpm. Calculate the voltage and frequency required so that the machine will run at 3200 rpm while developing a torque of 120Nm.

# SUMMARY OF CHAPTER

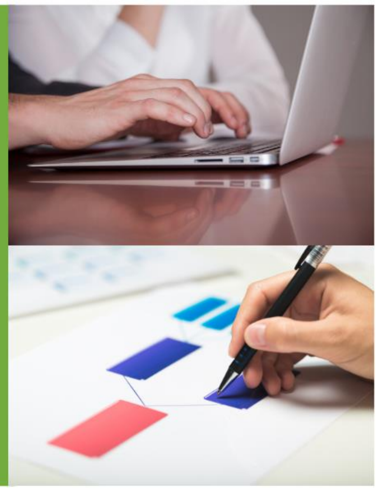

**Success is not final, Failure is not Fatal, It is the courage to continue that counts.**

**MOTIVATION QUOTES**

Understand and apply the speed control methods of DC Shunt/Separately Excited Motors.

Apply and analyze the principles of solid state control (thyristor and chopper control).

Evaluate the motor efficiency using different control methods related to energy saving.



# 03

# SPEED CONTROL OF DIRECT CURRENT (DC) MOTOR

# SPEED CONTROL OF DC MOTOR

## 3.1 INTRODUCTION

- The DC machine is popular in a number of drive applications due to its simple operation and control. The starting torque of DC machines is large, which is the main reason for using it in several traction applications.
- A large number of appliances and power tools used at home, such as circular saws and blenders, are DC machines.
- The main components of the DC machine: field circuit, armature circuit, commutator, and brushes.
- DC motors have several intrinsic properties, such as can be controlled, their ability to deliver high starting torque, near-linear performance and widely used in applications such as actuation, manipulation, and traction.
- DC motors have drawbacks that may restrict their use in some applications. For example, DC motors are relatively high-maintenance machines due to their commutation mechanisms, large and expensive compared to other motors, such as the induction, may not be suitable for high-speed applications due to the presence of the commutator and brushes and because of the electrical discharging between the commutator segments and brushes, DC machines cannot be used in clean or explosive environments unless they are encapsulated. Nevertheless, DC motors still hold a large share of the ASD (adjustable speed drive) market.

# SPEED CONTROL OF DC MOTOR

## 3.1 INTRODUCTION

- Newer designs of dc motors have emerged that eliminate the mechanical commutator. E.g: Brushless DC motor.
- DC motors can be classified into four groups based on the arrangement of their field windings. Motors in each group exhibit distinct speed-torque characteristics and are controlled by different means. These four groups are:

  1.Separately excited machines.
  2.Shunt machines.
  3.Series machines.
  4.Compound machines.

# SPEED CONTROL OF DC MOTOR

## 3.2 DC SHUNT/SEPARATELY EXCITED MOTORS

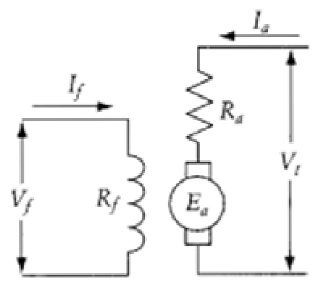



***Figure 3.1: Equivalent Circuit of a DC Motor in Steady State Operation***

Notes:

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

$$I_a = \frac{V_t - E_a}{R_a}$$

$$P_d = E_a I_a = T_d \omega$$

$P_d$ is power developed
$T_d$ is torque developed

Basic Equations:

$$T_d = K\phi \frac{V_t - E_a}{R_a}$$

$$E_a = K\phi\omega$$

$$T_d = K\phi I_a$$

$$T_d = K\phi \frac{V_t - K\phi\omega}{R_a}$$

where $\phi$ is the flux, which is almost proportional to $I_f$ for separately excited motors. The constant K is dependent on design parameters such as the number of poles, number of conductors, and number of parallel paths.

$$\omega = \frac{V_t}{K\phi} - \frac{R_a}{(K\phi)^2} T_d = \omega_0 - \Delta\omega$$

$$\omega = \frac{V_t}{K\phi} - \frac{R_a}{K\phi} I_a = \omega_0 - \Delta\omega$$

# SPEED CONTROL OF DC MOTOR

## 3.2 DC SHUNT/SEPARATELY EXCITED MOTORS

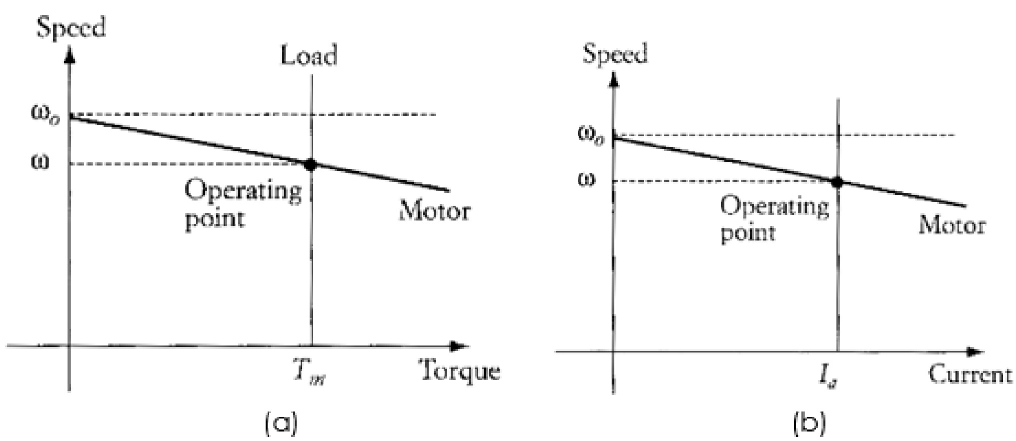



***Figure 3.2: (a) Speed-Torque Characteristics, (b) Speed-Current Characteristics of DC Separately Excited Motor***

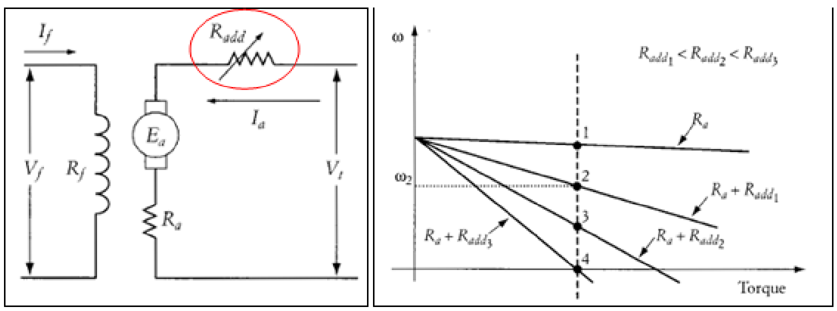
There are **THREE (3)** methods to control the speed of DC separately excited motor by: -

1. Adding resistance in armature circuit. When a resistance is inserted in the armature circuit, the speed drop $\Delta\omega$ increases and the motor speed decreases.
2. Adjusting armature voltage or terminal voltage. Reducing the armature voltage, $V_t$ of the motor reduces the motor speed.
3. Adjusting field voltage or field flux. Reducing the field voltage reduces the flux $\phi$ and the motor speed increases.

**Note:** We cannot control the motor speed by increasing the armature or field voltages beyond the rated value. Only voltage reduction can be implemented

# SPEED CONTROL OF DC MOTOR

## 3.3 METHOD 1: CONTROLLING SPEED BY ADDING RESISTANCE




(a) (b)

***Figure 3.3: (a) A Setup for speed change by adding an armature resistance in DC motor, (b) Effect of adding an armature resistance on speed***

- By referring Figure 2.3 (a), assume that the field and armature voltages are constant.
- By referring Figure 2.3(b), at point 1, no external resistance is in the armature circuit.
- If a resistance $R_{add1}$ is added to the armature circuit, the motor operates at point 2, where the motor speed $\omega_2$

$$\omega_2 = \frac{V_t}{K\Phi} - \frac{R_a + R_{add_1}}{(K\Phi)^2} T_d = \omega_0 - \Delta\omega_2$$

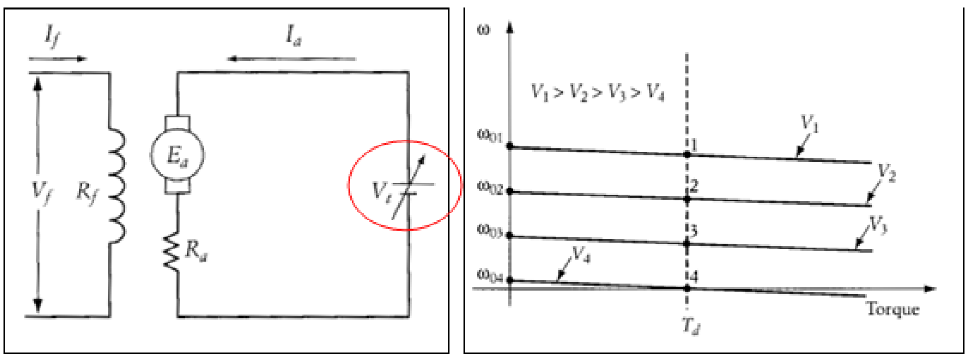
$$\omega_2 = \frac{V_t}{K\Phi} - \frac{R_a + R_{add_1}}{K\Phi} I_a = \omega_0 - \Delta\omega_2$$

- If the added resistance keeps increasing, the motor speed decreases until the system operates at point 4, where the speed of the motor is zero.
- The operation of the drive system at point 4 is known as "holding."
- It is quite common to operate the motor under electrical holding conditions in applications such as robotics and actuation.

**Summary:** Resistance in armature circuit → When a resistance is inserted in the armature circuit, the speed drop, Δω increase and the motor speed decrease
$R_{add} \uparrow, N_S \downarrow$

# SPEED CONTROL OF DC MOTOR

## 3.4 METHOD 2: CONTROLLING SPEED BY ADJUSTING ARMATURE VOLTAGE




(a) (b)

***Figure 3.4: (a) A setup for changing speed by adjusting the armature voltage, (b) Motor characteristics when armature voltage change***

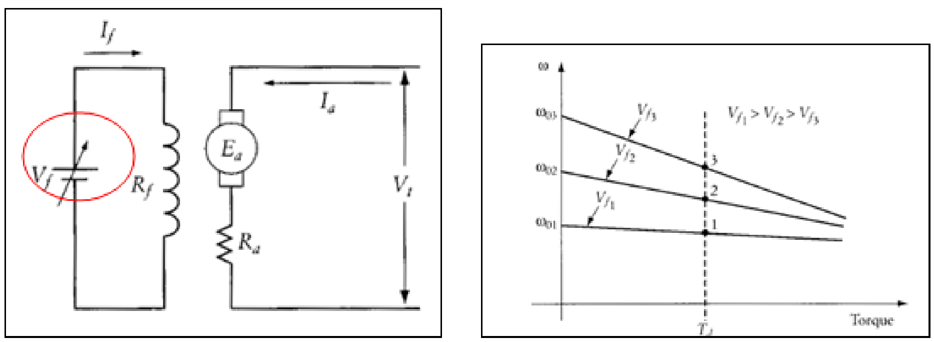
- This method is highly efficient and stable and is simple to implement.
- A setup for changing speed by adjusting the armature voltage
- The only controlled variable is the armature voltage of the motor, which is depicted as an adjustable-voltage source.
- Note that we are assuming the field voltage is unchanged when the armature voltage varies.
- Electric holding can be done if the armature voltage is reduced until $\Delta\omega$ is equal to $\omega_0$.

**Summary:** When the armature voltage, $V_t$ is reduced, the no-load speed $\omega_0$ is also reduced and also motor speed reduces

$$V_t \downarrow, N_S \downarrow$$

# SPEED CONTROL OF DC MOTOR

## 3.5 METHOD 3: CONTROLLING SPEED BY ADJUSTING FIELD VOLTAGE




(a) (b)

***Figure 3.5: (a) A setup for changing speed by adjusting the field voltage, (b) Motor characteristics when field voltage change***

- The no-load speed is inversely proportional to the flux.
- When motor speed is controlled by adjusting the field current, the following considerations should be kept in mind:

1. The field voltage must not exceed the absolute maximum rating.
2. Since dc motors are relatively sensitive to variations in field voltage, large reductions in field current may result in excessive speed.
3. Because the armature current is inversely proportional to the field flux ($I_a = T_d / K\emptyset$), *reducing the field results in an increase in the armature current* (assuming that the load torque is unchanged).

**Summary:** Reducing the field voltage, the field current,$I_f$ the flux, ϕ will reduces and the motor speed increases

$$V_f \downarrow, I_f \downarrow, N_S \uparrow$$

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

Solid-state control is used for enhanced efficiency and for versatile operation of electric drive systems. For dc machines, converters are often used in the armature circuit to control the terminal voltage of the motor. In some cases, the converter is also used to control the field voltage.

In this chapter, we will analyse the DC separately excited motor when energized by:

- Single-Phase, Half-Wave Drives
- Single-Phase, Full-Wave Drives

} RECTIFIER

- 1st Quadrant – Type A
- 2nd Quadrant – Type B
- 3rd Quadrant – Type C
- 4th Quadrant – Type D

} CHOPPER

**1. Single-Phase, Half Wave Drives**

- The armature circuit of the motor is connected to the converter, which is fed from an ac source. The field circuit of the motor is excited from the ac source through a full wave rectifier circuit, which may contain filters.
- The converter in this case is a simple **SCR triggered by a control circuit** not shown in the figure below.

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

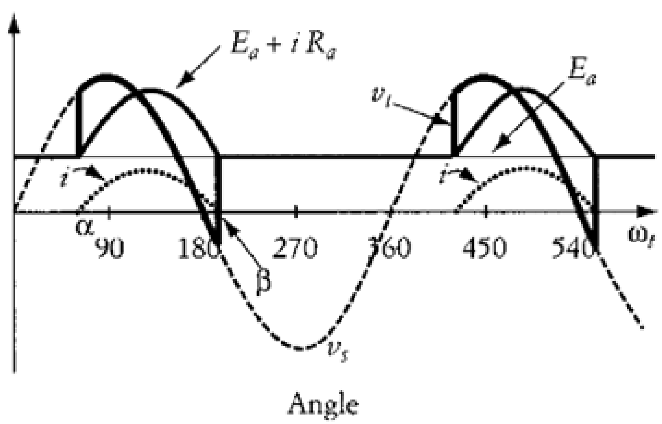



*Figure 3.6: A Single-Phase, Half-Wave SCR Drive Waveform*

### 2. Single-Phase, Full Wave Drives

- The switching of the SCRs is dependent on the polarity of the source voltage, $V_s$. The current $i_1$ (solid lines) flows when the ac waveform of the source voltage is in the positive half-cycle, and SCRs $S_1$ and $S_2$ are triggered.
- Similarly, current $i_2$ (dashed lines) flows when the waveform of the source voltage is in the negative half, and $S_3$ and $S_4$ are triggered.
- In either half of the cycle, the current will flow in the same direction inside the motor. Refer Figure below.

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

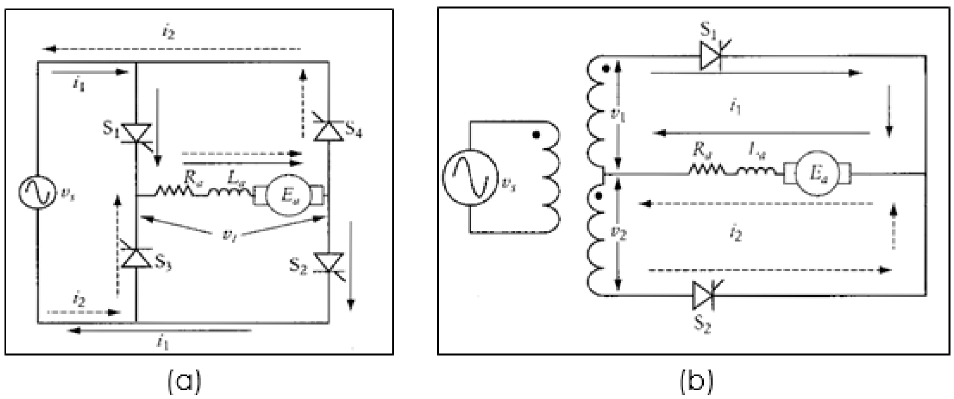



***Figure 3.7: Full-Wave Drive (a) Using Four SCR Bridge, (b) Using Two SCRs and a Center-Tap Transformer***

- Figure 2.7(b) shows center-tap transformer as another alternative where two SCRs are used.
- The secondary of the transformer should have double the voltage rating of the motor; that is, $V_1 = V_2$ = rated armature voltage.
- When the source voltage $V_s$, is in the positive half of its cycle and $S_1$ is triggered, $i_1$ flows in the upper half of the transformer's secondary windings.
- When the source voltage is in the negative part and $S_2$ is closed, $i_2$ flows in the lower half of the secondary windings.
- Again, in either half of the source waveform, the armature current of the machine is unidirectional.
- The equation of armature circuit is:

$$\frac{V_{max}}{\pi}[\cos(\alpha) - \cos(\beta)] = \frac{\gamma}{\pi}E_a + R_a I_{ave}$$

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

$$\frac{V_{max}}{\pi}[\cos(\alpha) - \cos(\beta)] = \frac{\gamma}{\pi}K\phi\omega + R_a I_{ave}$$

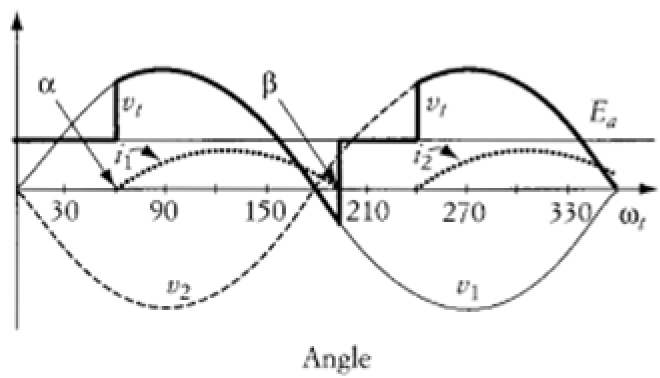



*Figure 3.8: A Single-Phase, Full-Wave SCR Drive Waveform*

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

<u>SUMMARY OF RECTIFIER</u>

$$Back\ EMF\ @\ Speed\ Voltage, E_g = K_v \omega I_f$$

$$Torque\ developed\ by\ the\ motor,\ T_d = K_v I_f I_a = B_w + T_L$$

$$Armature\ Voltage,\ V_a = I_a R_a + E_g = I_a R_a + K_v \omega I_f$$

$$\omega = \frac{2\pi}{60} N(rpm)$$ In rad/sec

$$N = \frac{60}{2\pi} \omega(rad/sec)$$ In rpm

**Single Phase Drive**

For continuous current, armature voltage,

$$V_a = \frac{2V_m}{\pi} \cos \alpha_a$$

$$I_a = \frac{V_a - E_g}{R_a}$$

$$V_f = \frac{2V_m}{\pi} \cos \alpha_f$$

Single phase half wave converter drives ($0 \leq \alpha \leq \pi$)

$$V = \frac{V_m}{2\pi}(1 + \cos \alpha)$$

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

Single phase semi-converter drives ($0 \le \alpha \le \pi$)

$$V = \frac{V_m}{\pi}(1 + \cos\alpha)$$

Single phase full converter drives

$$V = \frac{2V_m}{\pi}\cos\alpha$$

**Three Phase Drive**

Three phase drive

$$V_a = \frac{3V_{mL-L}}{\pi}\cos\alpha_a$$

$$I_a = \frac{V_a - E_g}{R_a}$$

$$V_f = \frac{2V_m}{\pi}\cos\alpha_f$$

Three phase half wave converter drives ($0 \le \alpha \le \pi$)

$$V = \frac{3\sqrt{3}V_m}{2\pi}\cos\alpha$$

Three phase semi converter drives

$$V = \frac{3\sqrt{3}V_m}{2\pi}(1 + \cos\alpha)$$

Three phase full converter drives ($0 \le \alpha \le \pi$)

$$V = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

### 3. Chopper

There are two control strategies employed in DC chopper

a. **Time ratio control** - value of TON/T is varied. This is effected in two ways-variable frequencies operation & constant frequency operation.

1. TON or TOFF is kept constant
2. TON or TOFF are varied

b. **Current Limit Control** - the chopper is switched ON and OFF so that the current in the load is maintained between two limit. When the current exceeds upper limit, the chopper switched OFF. When the current reached lower limit, the chopper switched ON. During the OFF period the load current freewheels and decreases exponentially.

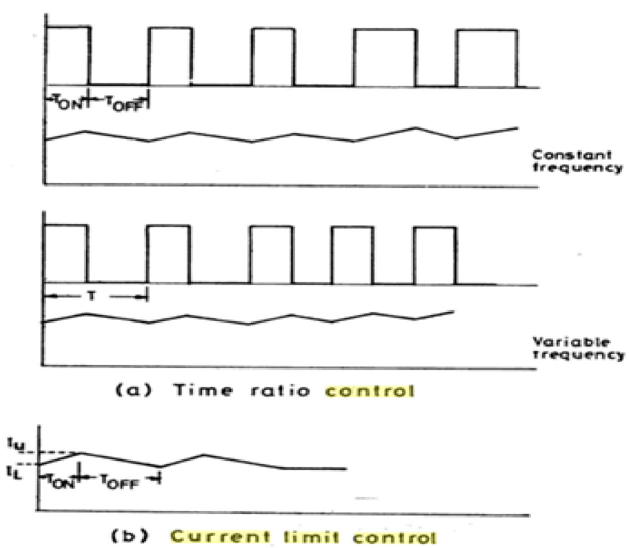



*Figure 3.9: Control Strategies of a Chopper*

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

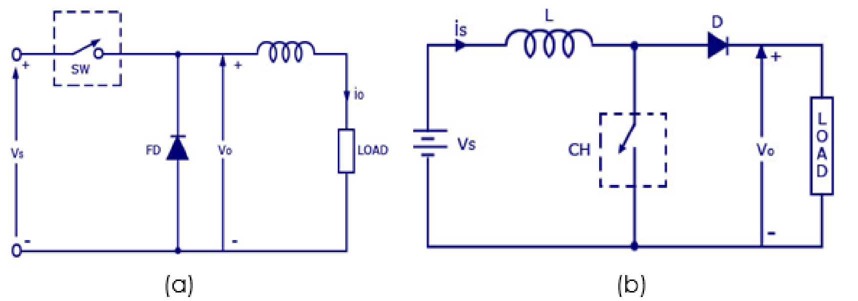



*Figure 2.10: Chopper Circuit – Load is DC Motor (a) Series Motor, (b) Separately Excited Motor*

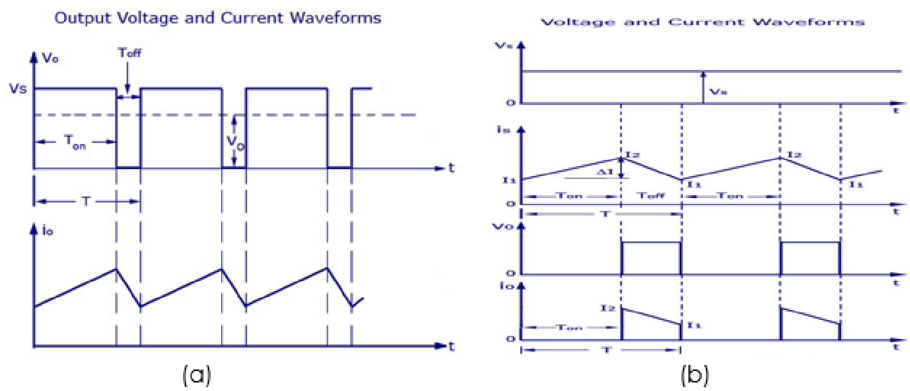



***Figure 3.10: Chopper Circuit – Output Waveform (a) Series Motor, (b) Separately Excited Motor***

Average load Voltage is given by

$V_0 = T_{on}/(T_{on} + T_{off}) * Vs = (T_{on}/T)\, V = A\, V_s$

$T_{on}$ : on -time

$T_{off}$ : off- time

$T = T_{on} + T_{off}$ = chopping period

$A = T_{on}/T$ = duty cycle

So we know that the load voltage can be controlled by varying the duty cycle A. equation above shows that the load voltage is independent of load current it can be also written as

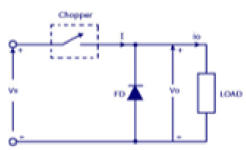
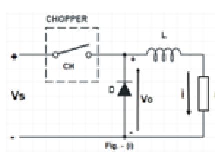
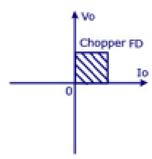
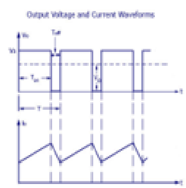
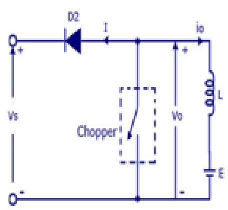
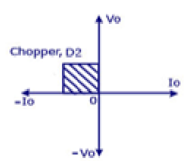
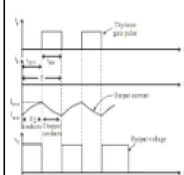
$V_0 = f.\, T_{on}.V_s$

$f = 1/T$ = chopping frequency

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

**SUMMARY OF CHOPPER TYPE**

| Type | Chopper Configuration | $E_a$-$I_a$ Characteristics | Function | Formula/Notes |
|---|---|---|---|---|
| 1st Quadrant (Step Down Chopper)<br>TYPE A | <br> | - Forward motoring<br>- Forward torque apply<br>- +ve speed<br>- Rectification<br> | - Inductor stores energy (magnetic field) → charged batteries<br>- S1 ON (conduct): current flow between +ve & -ve supply through L1.<br>- S1 OFF: Current drop and L1 produce back emf to keep constant current flowing series to each other. D1 forward biased, current through load.<br>$V_a = V_O$ for $S_1$<br>$V_a = 0$ for $S_1$ OFF & $D_1$ ON | $V_O < V_S$<br>- $V_O$ and $I_O$ always +ve<br> |
| 2nd Quadrant Regeneration<br>TYPE B |  | - Forward braking<br>- Reversed torque apply<br>- -ve speed<br>- Inversion<br> | - Chopper ON, $V_O$=0, Load voltage E drives current through L & chopper<br>- L stores energy during $T_{ON}$<br>- Chopper OFF, D forward biased & conducting & power start flowing to the source.<br>- $V_O$=+ve, $I_O$=-ve, power flow from load to source<br>- Step-up chopper – Regenerative braking<br>$V_a = 0$ for $S_1$<br>$V_a = V_O$ for $S_1$ OFF & $D_1$ ON | $V_O = E + L\frac{di}{dt}$<br>$V_O > V_S$<br> |

# SPEED CONTROL OF DC MOTOR

## 3.6 SOLID STATE CONTROL (THYRISTOR CONTROL)

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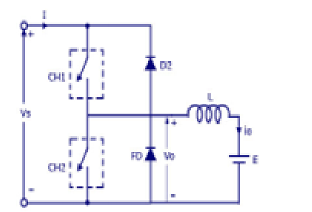
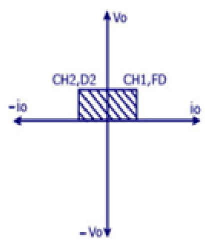
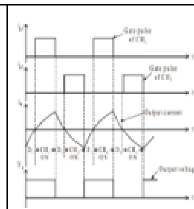
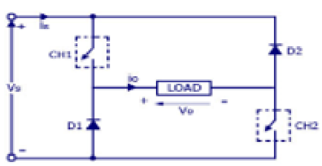
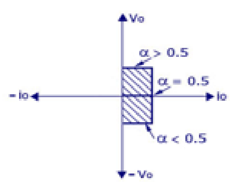
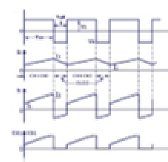
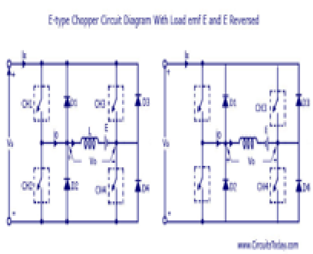
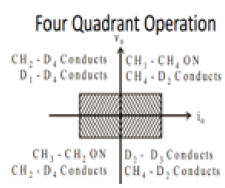
<tr><td>Two Quadrant Chopper<br>TYPE C</td><td>
</td><td>
</td><td>$e_a = V_O$ for $S_1$ @ $D_2$ ON<br>$e_a = V_O$ for $S_2$ @ $D_1$ ON<br>$i_a > 0$ for $S_1$ @ $D_1$ ON<br>$i_a < 0$ for $S_2$ @ $D_2$ ON</td><td></td></tr>
<tr><td>Two Quadrant Chopper<br>TYPE D</td><td>
</td><td>
</td><td>$V_a = +V_O$ for $S_1$ & $S_2$ ON<br>$V_a = -V_O$ for $S_1$ & $S_2$ OFF & $D_1$ & $D_2$ ON</td><td></td></tr>
<tr><td>Four Quadrant Chopper<br>TYPE E</td><td>
</td><td>
</td><td>$S_4$ On, $S_3$ OFF, $S_1$ & $S_2$ Operated<br>$V_a > 0$, $I_a$ reversible<br>$S_2$ ON & $S_1$ OFF, $S_3$ & $S_4$ Operated<br>$V_a < 0$ $I_a$ reversible</td><td></td></tr>
</table>

# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

**Example 3.1:**

A 150 V, dc shunt motor drives a constant-torque load at a speed of 1200 rpm. The armature and field resistances are 1Ω and 150Ω, respectively. The motor draws a line current of 10 A at the given load.

a. Calculate the resistance that should be added to the armature circuit to reduce the speed by 50%.

b. Assume the rotational losses to be 100 W. Calculate the efficiency of the motor without and with the added resistance.

c. Calculate the resistance that must be added to the armature circuit to operate the motor at the holding condition.

Solution:

Given: V=150V, $N_s$=1200rpm, $R_a$=1Ω, $R_f$=150Ω, I=10A

a. The resistance that should be added

$$I_{a_1} = I - I_f = 10 - \frac{150}{150} = 9 \text{ A}$$

the speed equations at these two operating points are

$$E_{a_1} = K\phi\omega_1 = V - I_{a_1}R_a$$

$$E_{a_2} = K\phi\omega_2 = V - I_{a_2}(R_a + R_{add_1})$$

The armature current is constant regardless of the value of the added resistance because $I_a = \frac{T_d}{K\emptyset}$ and $T_d$ and $\emptyset$ are constants. Hence, $I_{a1} = I_{a2}$.

# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

$$\frac{E_{a_1}}{E_{a_2}} = \frac{\omega_1}{\omega_2} = \frac{n_1}{n_2} = \frac{V - I_a R_a}{V - I_a(R_a + R_{add_1})}$$

$$\frac{1200}{0.5 \times 1200} = \frac{150 - 9 \times 1}{150 - 9 \times (1 + R_{add_1})}$$

$$R_{add_1} = 7.83\ \Omega$$

b. To calculate the motor efficiency, first calculate the input power

$$P_{in} = VI = 150 \times 10 = 1500\ \text{W}$$

$$\text{Losses before adding armature resistance} = 150 + 81 + 100 = 331\ \text{W}$$

$$\text{Losses after adding armature resistance} = 150 + 81\,(1 + 7.83) + 100 = 965.23\ \text{W}$$

$$\text{Efficiency without resistance} = \frac{1500 - 331}{1500}\,100 = 77.93\%$$

$$\text{Efficiency after adding resistance} = \frac{1500 - 965.23}{1500}\,100 = 35.66\%$$

c. To calculate the resistance to be added to the armature for the holding operation, set the motor speed equal to zero

$$K\phi\omega = V - I_a(R_a + R_{add}) = 0$$

$$R_{add} = \frac{V}{I_a} - R_a = \frac{150}{9} - 1 = 15.67\ \Omega$$

# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

**Example 3.2:**

A 150V DC shunt motor drives a constant-torque load at a speed of 1500rpm. The armature & field resistance is 2Ω & 150Ω respectively. The motor draws a line current of 10A. Assume that a resistance is added in the field circuit to reduce the field current by 20%. Calculate the armature current, motor speed, value of the added resistance & extra field losses.

Solution:
Given: V=150V, $N_s$=1500rpm, $R_a$=2Ω, $R_f$=150Ω, I=10A

$$I_{a_1} = I - I_{f_1} = 10 - \frac{150}{150} = 9 \text{ A}$$

Since the load torque is constant,

$$T_d = K\phi_1 I_{a_1} = K\phi_2 I_{a_2}$$

$$I_{a_2} = \frac{\phi_1}{\phi_2} I_{a_1}$$

Assume that the flux is linearly proportional to the field current

$$I_{a_2} = \frac{I_{f_1}}{I_{f_2}} I_{a_1} = \frac{1}{0.8} 9 = 11.25 \text{ A}$$

# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

Notice that the armature current is increased by 25%. To calculate the speed, consider the two equations

$$E_{a_1} = K\phi_1\omega_1 = V - I_{a_1}R_a$$

$$E_{a_2} = K\phi_2\omega_2 = V - I_{a_2}R_a$$

Or

$$\frac{\emptyset_1}{\emptyset_2}\frac{n_1}{n_2} = \frac{V - I_{a1}R_a}{V - I_{a2}R_a}$$

$$\frac{1}{0.8}\frac{1500}{n_2} = \frac{150 - 9(2)}{150 - 11.25(2)}$$

$$n_2 = 1812rpm$$

The result is a 20.8% increase in speed.
The value of the resistance that should be inserted in the field circuit can be calculated using Ohm's Law:

$$V_f = V_t = I_{f_1}R_f = I_{f_2}(R_f + R_{add})$$

$$(1)(150) = 0.8(150 + R_{add})$$

$$R_{add} = 37.5\ \Omega$$

The losses due to $R_{add}$ are

$$P = I_{f_2}^2 R_{add} = (0.8)^2 \times 37.5 = 24\ \text{W}$$

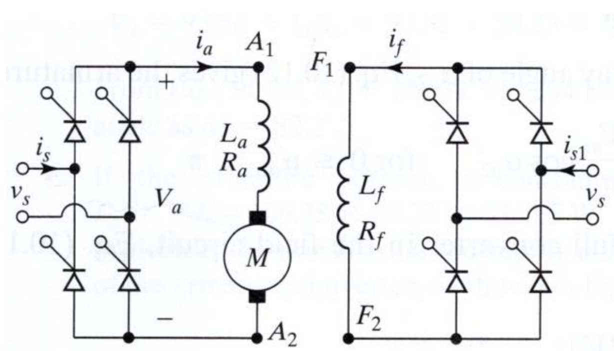
Note that the additional losses are small when a resistance is added to the field circuit. Therefore, the technique is acceptable in industry even when solid-state field control devices are available.

# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

**Example 3.3:**

The speed of a separately excited motor is controlled by a single phase semiconverter in figure below. The field current, which is also controlled by semiconverter, is set to the maximum possible value. The AC supply voltage to the armature and field converters is single phase, 220V, 50Hz. The armature resistance is $R_a$=0.25Ω, the field resistance is $R_f$=175Ω and the motor voltage constant is $K_v$=0.7032V/A rad/s. the load torque is $T_L$=45Nm at 1000 rpm. The viscous friction and no-load losses are negligible. The inductances of the armature and the field circuits are sufficient to make the armature and field currents continuous and ripple free. Calculate the field current If and the delay angle αa of the converter in the armature circuit.



# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

Solution:

$Vs = 220V$ , $Ra = 0.25\ \Omega$, $R_f = 175\ \Omega$, $T_L = 45$ Nm, $Kv = 0.7032\ \frac{V}{A}$

$Vm = \sqrt{2}\ X\ V_S = \sqrt{2}\ X\ 220 = 311.13V$

$\omega = \frac{1000\pi}{30} = 104.72\ rad/s$

a) From equation, $V_f = \frac{2Vm}{\pi}\cos\alpha_f$ , the maximum field current, $I_f$ is obtained for a delay angle of $\alpha_f = 0^0$

$V_f = \frac{2Vm}{\pi} = \frac{2 \times 311.13}{\pi}$

=198.07 V

The field current is;

$I_f = \frac{V_f}{R_f} = \frac{198.07}{175} = 1.13\ A$

b) From equation, $T_L = K_V I_f I_a$

$Ia = \frac{T_L}{KvI_F}$

$= \frac{45}{0.7032 \times 1.13}$

= 56.63 A

# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

From equation, $Eg = Kv\omega I_f = 0.7032 \times 104.72 \times 1.13 = 83.21V$

From equation, $Va = RaIa + Eg \quad = (0.25 \text{ X } 56.63) + 83.21$

$= 14.16 + 83.21$

$= 97.37 \text{ V}$

For semiconverter drives:

From equation $Va = \frac{Vm}{\pi}(1 + \cos\alpha_a)$

$97.37 = \frac{311.13}{\pi}(1 + \cos\alpha_a)$

$97.37 = 99.04(1 + \text{COS } \alpha_a)$

$0.983 = 1 + \text{COS}\alpha_a$

$\cos\alpha_a = 0.983\text{-}1$

$\alpha_a = \cos^{-1}(-0.017)$

$= \mathbf{90.97}^{\circ}$

# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

**Example 3.4:**

A three-phase squirrel cage induction motor with 4 poles, 10hp, 600V, 60Hz develops a torque of 120Nm at a speed of 1500rpm. If the motor is excited at a frequency of 30Hz, calculate

i. Stator voltage needed to maintain the same flux in the motor

ii. The new speed at 120N-m torque

**Solution**

i. Stator voltages reduce by frequency range:

$$V_{s2} = \frac{fnew}{fold} \times Vt$$

$$V_{s2} = \frac{30}{60} \times 600$$

$$= 300V$$

ii. The new speed at 120N-m torque

Synchronous speed:

$$N_s = \frac{120fold}{P}$$

$$= \frac{120 \times 60}{4}$$

$$= 1800rpm$$

# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

Difference between speed at 120Nm and synchronous speed:

$$N_1 = N_s - N_{r120}$$

$$N_1 = 1800 - 1500 = 300rpm$$

Synchronous speed at 30Hz:

$$N_{s2} = \frac{120\,(30)}{4} = 900\ rpm$$

New speed at 120Nm Torque:

$$N_2 = N_{s2} - N_1 =$$

$$N_2 = 900 - 300 = 600rpm$$

# SPEED CONTROL OF DC MOTOR

## 3.7 CALCULATION EXAMPLE

**Example 3.5:**

A three-phase, six-pole, Y-connected, 480 V induction motor is driving a 300 Nm constant-torque load. The motor has the following parameters:

$N_l / N_2 = 1$, Protational = 1 kW

The motor is driven by a slip energy recovery system. The triggering angle of the dc/ac converter is adjusted to 120°. Ignore all core losses. Verify that the power developed is 19.85kW

**Solution**

$$n_1 = \frac{120f}{p} = \frac{120(60)}{6} = 1200rpm$$

$$n = n_1\left(1 + \frac{N_1}{N_2}\cos\alpha\right) = 1200(1 + 1\cos 120°) = 600rpm$$

To compute the current in the dc link, you need to compute the output power $P_{out}$ and developed power $P_d$

$$P_{out} = T_{out}\omega = 300\left(2\pi\frac{n}{60}\right) = 300\left(2\pi\frac{600}{60}\right) = 18.85kW$$

where $T_{out}$ is the shaft torque.

$$P_d = P_{out} + P_{rotational} = 18.85kW + 1kW = 19.85kW$$

# SPEED CONTROL OF DC MOTOR

## 3.8 REVIEW QUESTION

1. Identify THREE (3) methods of speed control for DC Separately Excited Motor
2. State THREE (3) advantages of DC Motor
3. Explain the effect when adding resistance in controlling the speed of DC Separately Excited Motor.
4. Sketch and label the circuit of single-phase half wave SCR drive.
5. Gives TWO (2) control strategies employed in DC chopper.
6. Construct circuit diagram of two quadrant operation of dc motors using chopper drives and sketch the quadrant operation of the circuit.

# SPEED CONTROL OF DC MOTOR

## 3.9 CALCULATION QUESTION

1. A 600V, DC shunt motor has armature and field resistance of 1.5Ω and 600Ω respectively. When the motor run unloaded, the line current is 3A and the speed is 1000rpm. Calculate torque developed at full load armature current of 50A, the motor speed if the load is constant-torque type when 3Ω resistance is added to the armature circuit and the motor speed if the field is reduced by 10%.

2. A 180V DC shunt motor drives a constant-torque load at a speed of 1800rpm. The armature & field resistance is 2Ω and 150Ω respectively. The motor draws a line current of 10A. Assume that a resistance is added in the field circuit to reduce the field current by 20%. Calculate armature current, motor speed and value of the added resistance at field circuit.

3. A 1hp, DC shunt motor is loaded by a constant torque of 10Nm. The armature resistance of the motor is 5Ω, and the field constant $K\phi$=2.5Vsec. the motor is driven by a half-wave SCR converter. The power source is 120V, 60Hz. The triggering angle of the converter is 60° and the conduction period is 150°. Calculate the motor speed and the developed power.

4. From question no. 3., now assume that the converter is a full-wave type. The triggering angle of the converter is 60°, and the conduction period is 150°. Calculate the motor speed and the developed power delivered to the load.

# SPEED CONTROL OF DC MOTOR

## 3.9 CALCULATION QUESTION

5. A DC separately excited motor has a constant torque load of 60Nm. The motor is driven by a full wave converter connected to a 120V, AC supply. The field constant of the motor $K\phi=2.5$ and the armature resistance is 2Ω. Calculate the triggering angle, $\alpha$ for the motor to operate at 200rpm. The motor current is continuous.

6. A 600V, DC Shunt motor has armature and field resistance of 1.5Ω and 600Ω respectively. When the motor runs unloaded, the line current is 3A and the speed is 1000rpm.
   a. Calculate motor speed when the load draws an armature current of 30A
   b. If the load is constant-torque type, what is the motor speed when 3Ω resistance is added to the armature circuit?
   c. Calculate the motor speed if the field is reduced by 10%.

7. A DC shunt motor drives a centrifugal pump at a speed of 1000rpm when the terminal voltage and line currents are 200V and 50A, respectively. The armature and field resistances are 0.1Ω and 100Ω respectively.

   a. Design a starting resistance for a maximum starting current of 120A in the armature circuit
   b. What resistance should be added to the armature circuit to reduce the speed to 800rpm?
   c. If the terminal voltage is reduced by 25%, what is the speed of the motor?

# SPEED CONTROL OF DC MOTOR

## 3.9 CALCULATION QUESTION

8. A 150V, DC shunt motor drives a constant-torque load at a speed of 1500rpm. The armature and field resistances are 2$\Omega$ and 150$\Omega$, respectively. The motor draws a line current of 10A at the given load.
   a. Calculate the resistance that should be added to the armature circuit to reduce the speed by 50%.
   b. Assume the rotational losses to be 100W. calculate the efficiency of the motor without and with the added resistance.
   c. Calculate the resistance that must be added to the armature circuit to operate the motor at the holding condition

9. A 1hp, DC shunt motor is loaded by a constant torque of 20Nm. The armature resistance of the motor is 4Ω, and the field constant $K\phi$=2.5Vsec. the motor is driven by a full-wave SCR converter. The power source is 200V, 60Hz. The triggering angle of the converter is 60° and the conduction period is 150°. Calculate the motor speed and the developed power.

# SPEED CONTROL OF DC MOTOR

## 3.9 CALCULATION QUESTION

10. A 240V DC shunt motor has an armature resistance of 0.2Ω. when the armature current is 40A, the speed is 1000rpm. (a) Find additional resistance, $R_{add}$ to be connected in series with armature to reduce the speed to 600rpm. Assume the armature current remains the same. (b) If the current decreases to 20A (with resistance $R_{add}$ connected) find the new speed of the motor.

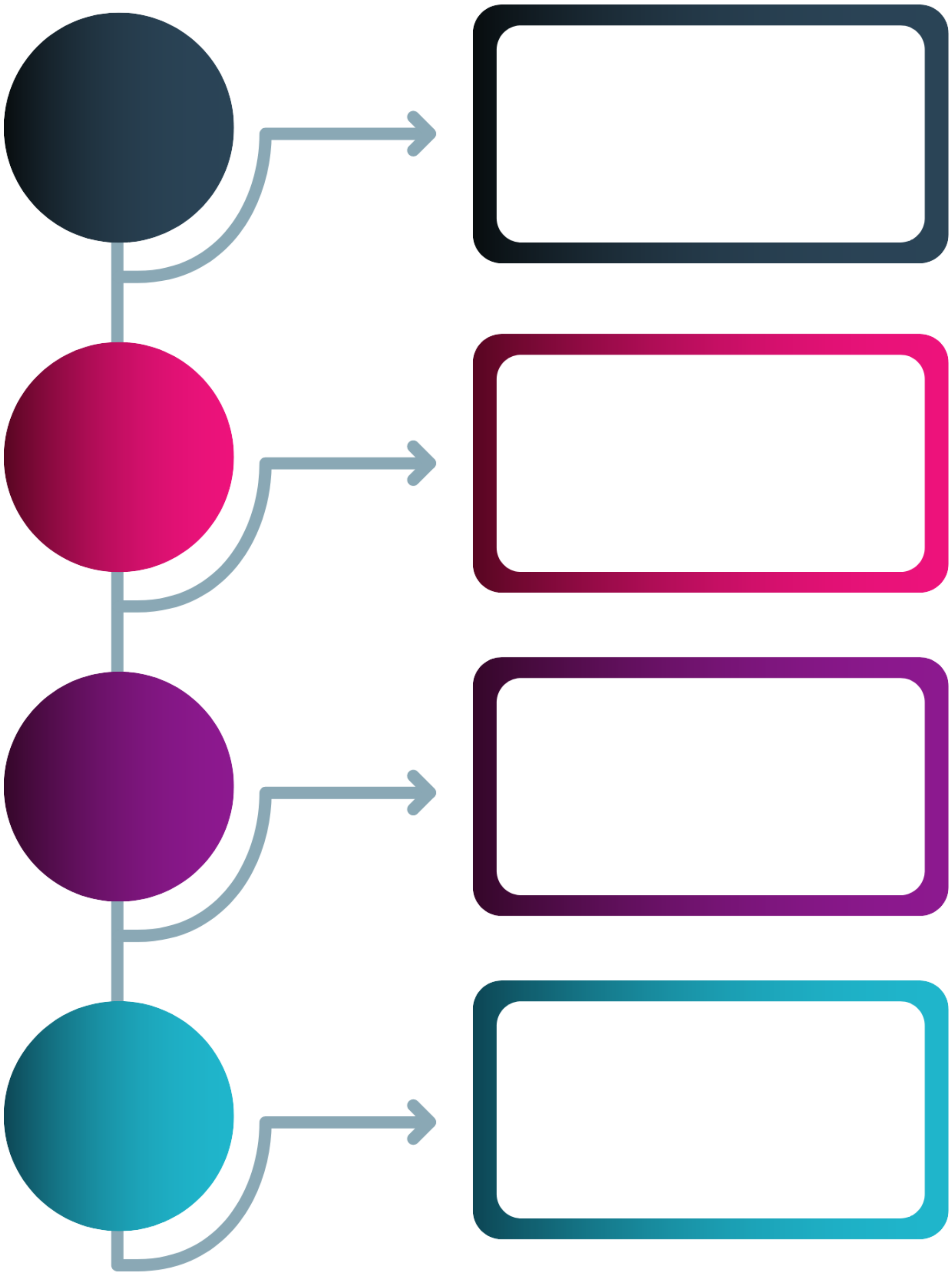
11. A 300V DC Shunt motor runs at 1600rpm when taking an armature current of 40A. The armature resistance is 0.5Ω. it is required to:

(a) Calculate the speed when a resistance is inserted in the field circuit as to reduce the flux to 60% of its nominal value (flux weakening)

(b) Calculate the speed when the field resistance is decrease to a value such that the flux is increases to 120% of its nominal value.

Assume that the armature current remains constant in both cases.

# SUMMARY OF CHAPTER



# SUMMARY OF CHAPTER

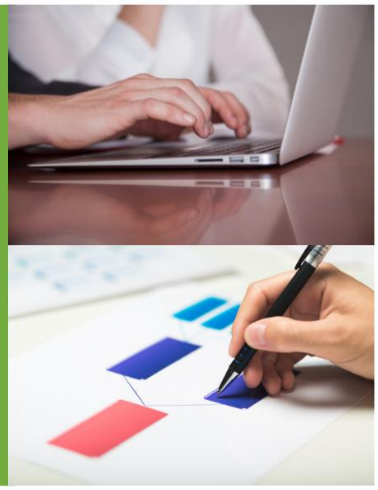

# Don't focus on the pain, focus on the progress.

## MOTIVATION QUOTES

Understand and apply the speed control methods of AC Motor/Induction Motor.

Apply and analyze the principles of voltage/frequency control and Slip Energy Recovery (SER)

Evaluate the motor efficiency using different control methods related to energy saving.

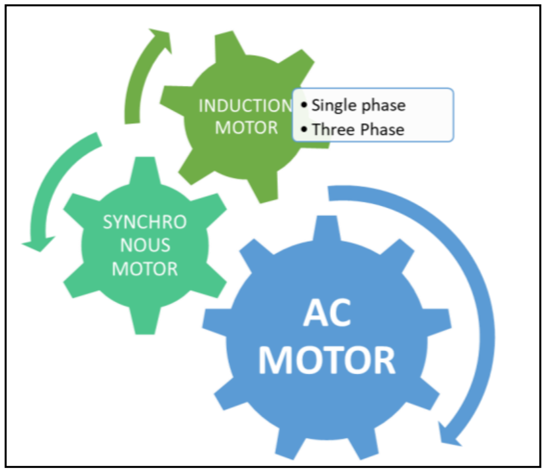


04

# SPEED CONTROL OF ALTERNATIVE CURRENT (AC) MOTOR

# SPEED CONTROL OF AC MOTOR

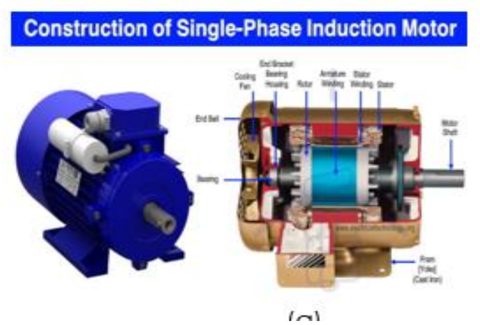
## 4.1 INTRODUCTION




- An AC motor is an electric motor driven by an alternating current (AC). The AC motor commonly consists of two basic parts, an outside stator having coils supplied with alternating current to produce a rotating magnetic field, and an inside rotor attached to the output shaft producing a second rotating magnetic field. The rotor magnetic field may be produced by permanent magnets, reluctance saliency, or DC or AC electrical windings.
- The two main types of AC motors are induction motors and synchronous motors.
- The induction motor (or asynchronous motor) always relies on a small difference in speed between the stator rotating magnetic field and the rotor shaft speed called slip to induce rotor current in the rotor AC winding. As a result, the induction motor cannot produce torque near synchronous speed where induction (or slip) is irrelevant or ceases to exist.
- In contrast, the synchronous motor does not rely on slip-induction for operation and uses either permanent magnets, salient poles (having projected magnetic poles), or an independently excited rotor winding. The synchronous motor produces its rated torque at exactly synchronous speed.

# SPEED CONTROL OF AC MOTOR

## 4.1 INTRODUCTION



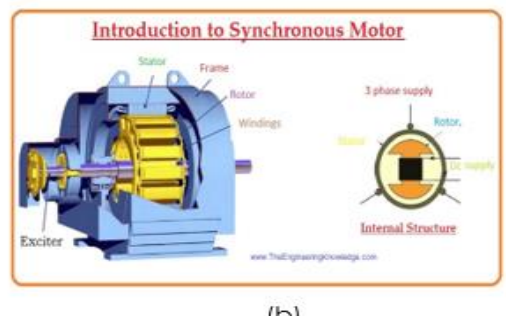




*Figure 4.1: Construction of (a) Single Phase Induction Motor, (b) Synchronous Motor*

| Synchronous motor | Induction motor |
|---|---|
| Construction is complicated | Construction is simpler , particularly in case of cage rotor |
| Not self starting | Self starting |
| Separate DC source is required for rotor excitation | Rotor gets excited by the induced e.m.f so separate source is not necessary |
| The speed is always synchronous irrespective of the load | The speed is always less than synchronous but never synchronous |
| Speed control is not possible | Speed control is possible though difficult |
| As load increases, load angle increases, keeping speed constant at synchronous | AS load increases , the speed keeps on decreasing |
| By changing excitation , the motor p.f can be changed from lagging and leading | It always operates at lagging p.f and p.f control is not possible |
| It can be used as synchronous condenser for p.f improvement | It can not be used as synchronous condenser |
| Motor is sensitive to sudden load changes and hunting results | Phenomenon of hunting is absent |
| Motor is costly and requires frequent maintenance | Motor is cheap , especially cage rotors and maintenance free |

# SPEED CONTROL OF AC MOTOR

## 4.2 INDUCTION MOTOR (IM)

- About 65% of the electric energy in the United States is consumed by electric motors. In the industrial sector alone, about 75% of the total energy is consumed by motors, and over 90% of them are induction machines.
- The main reasons for the popularity of the induction machines are that they are rugged, reliable, easy to maintain, and relatively inexpensive.
- Their power densities (output power to weight) are higher than those for DC motors.

$$n_s = \frac{60f}{pp} = 120\frac{f}{p}\ \text{rpm}$$

- The difference between the rotor speed (n or w) and the synchronous speed ($n_s$ or $\omega_s$) is known as the slip, s

$$s = \frac{\Delta n}{n_s} = \frac{\Delta\omega}{\omega_s} = \frac{n_s - n}{n_s} = \frac{\omega_s - \omega}{\omega_s}$$

- IM requires variable-frequency power electronic drive for optimal speed control – our topic
- IM will always run at a speed lower than synchronous speed. NS>NR → Speed fall magnetic field produces an induces voltage in rotor winding
- Three phase AC current pass into the stator produce rotating magneting field, current will be induces in the bar of squirrel cage and rotor starting rotated, electricity induced on a rotor

# SPEED CONTROL OF AC MOTOR

## 4.2 INDUCTION MOTOR (IM)

- Eddy current minimum: $Slip = (N_S - N_R)/N_S$
- Ns α F, when frequency (f) is increase, synchronous speed($N_S$) will increase and rotor speed($N_R$).
- IM use method Pulse width modulation (PWM) and Pulse Width Controller (PWC) to control their signal that send to motor as a driver.
- **PWM** → method to control output voltage without disturbance by using AC motor control. Convert digital signal to analog output voltage.
- **PWC** → method to change pulse width. One multivibrator and amplifier used. Control the width of a pulse signal.
- Thyristor circuit: thyristor switching circuits to control much larger loads like lamps, motor, heaters etc
- How to turn on thyristor? By inject a small trigger pulse of current (not continuous current - μs) into the gate (G) terminal when the thyristor forward direction, Anode (A) is positive respect to the Cathode (K), for regenerative latching to occur.
- When thyristor start conduct it continuous to conduct even no gate signal until the anode current decrease below the devices holding current (IH) → auto turn off.
- Thyristor cannot be used for amplification @ controlled switching. Thyristor used for high power switching application that operate only in the switching mode.
- While stator voltage control is method used to control speed of IM. The speed of three phase IM can be varied by varying the supply voltage

# SPEED CONTROL OF AC MOTOR

## 4.2 INDUCTION MOTOR (IM)

- The torque developed is proportional to the square of the supply voltage and the slip at the maximum torque is independent of the supply voltage
- The variation in the supply voltage foes do not alter the synchronous speed ($N_S$) of the motor.

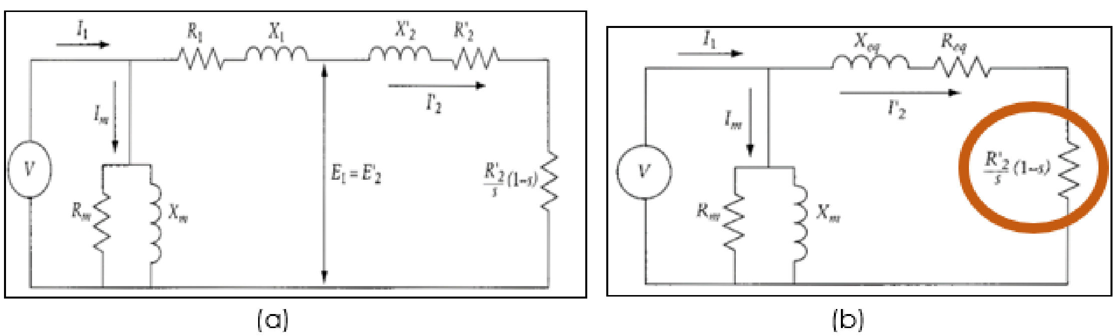



***Figure 4.2: (a) Circuit for IM, (b) Equivalent Circuit for IM with the circle is represent the load of the motor, which includes the mechanical and rotational loads***

# SPEED CONTROL OF AC MOTOR

## 4.3 SPEED CONTROL METHOD OF INDUCTION MOTOR

- Starting torque slightly higher than its full-load torque, motor start carrying any load it can supply at full load. Torque of the motor for a given slip varies at the square of the applied voltage.
- If rotor is driven faster than Ns → run as generator (mechanical → electrical)
- By vary supplying voltage, speed can be controlled. The voltage is varied until the torque required by the load is developed at the desired speed. The torque developed is proportional to the square of the supply voltage and the current is proportional to the voltage.
- There are **FOUR (4)** methods to control the speed of induction motor by: -

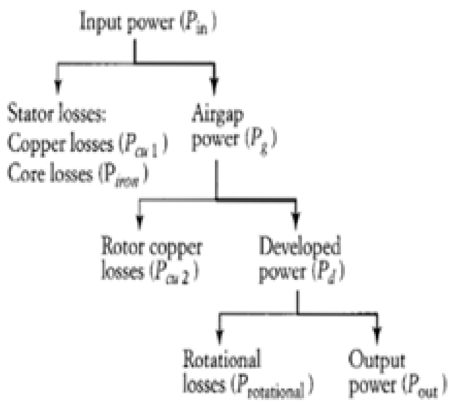
1. By connecting an external resistance in the stator circuit of the motor
2. Using auto transformer
3. Using a thyristor voltage controller
4. TRIAC controller

- Here, the simplified for each part of IM to controlling the speed: -

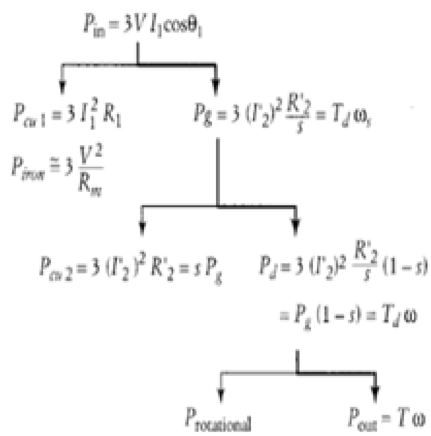
| ROTOR | STATOR |
|---|---|
| • Add an external resistance into rotor side circuit<br>• Applying cascade connection: thyristor circuit<br>• Injecting e.m.f into rotor side circuit of the motor<br>• Slip Energy Recovery (SER) | • By changing the supply voltage of the motor<br>• Changing the stator pole number of the motor<br>• Changing the frequency of the supply side of the motor |

# SPEED CONTROL OF AC MOTOR

## 4.4 POWER FLOW OF INDUCTION MOTOR




**Detailed power flow of the induction motor**




The motor efficiency η is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

# SPEED CONTROL OF AC MOTOR

## 4.5 CONTROLLING SPEED BY ADJUSTING THE STATOR VOLTAGE

- Several techniques can be used to change the stator voltage of the motor.
- One of them is using SCR connected back to back as shown in Figure 3.3. The circuit configuration of phase control is a full wave.
- In this circuit, the induction motor is connected to a three-phase supply voltage via back-to-back SCR pairs.
- For each phase, one SCR conducts the current in one direction (from the source to the motor), and the other SCR conducts the current in the second half of the cycle (from motor to source).
- If the triggering of these SCRs is controlled, the voltage across the stator terminals can change from zero to almost full voltage.
- As seen in equation below, the torque of the motor is proportional to the square of its stator voltage.

$$T_d = \frac{P_d}{\omega} = \frac{V^2 R'_2}{s\omega_s\left[\left(R_1 + \frac{R'_2}{s}\right)^2 + X_{eq}^2\right]}$$

- For the same slip and frequency, a small change in motor voltage results in a relatively large change in torque.
- A 10% reduction in voltage causes a 19% reduction in developed torque as well as the starting and maximum torques.
- The figure 3.4 shows two curves for two different values of the stator voltage. (Note that the slip at the maximum torque remains unchanged since it is not a function of voltage).
- For normal operation in the linear region, the figure shows that the motor speed can be modestly changed when the voltage is altered.
- However, a wide range of speed control cannot be accomplished by this technique.
- Nevertheless, it is an excellent method for reducing starting current and increasing efficiency during light loading conditions.
- The starting current is reduced since it is directly proportional to the stator voltage.
- The losses are reduced, particularly core losses, which are proportional to the square of the voltage.

# SPEED CONTROL OF AC MOTOR

## 4.5 CONTROLLING SPEED BY ADJUSTING THE STATOR VOLTAGE

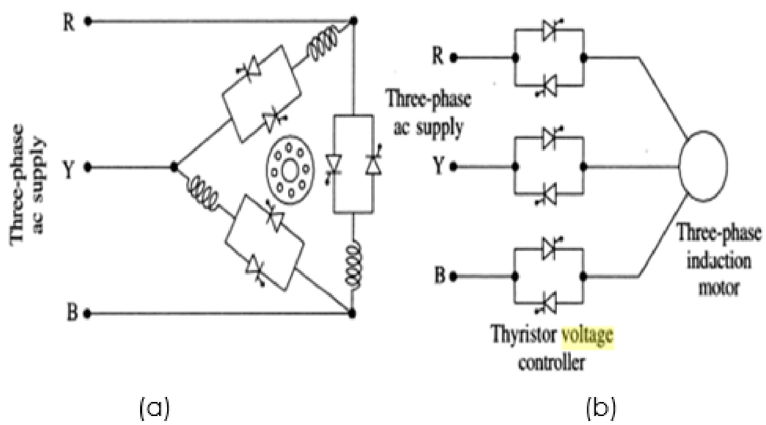
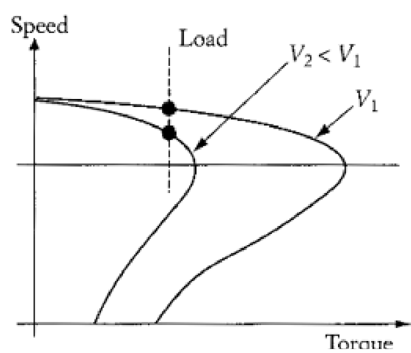



*Figure 4.3: Three Phase AC Voltage Controller Circuits (a) Delta Connection, (b) Star Connection*

**Impact of voltage on motor speed**




Keep in mind that the terminal voltage cannot exceed the rated value to prevent the damage of the windings' insulation. Thus, this technique is only suitable for speed reduction below the rated speed.

*Figure 4.4: Speed-Torque Characteristics – Impact of Voltage on Motor Speed*

**Summary:** Adjusting Stator Voltage → the motor speed decrease, Torque decrease, Starting Current, $I'_2$ and the efficiency is increses

$$V_s \downarrow, N_S \downarrow$$

# SPEED CONTROL OF AC MOTOR

## 4.6 CONTROLLING SPEED BY ADJUSTING THE SUPPLY FREQUENCY

- In steady state, the induction motor operates in the small-slip region, where the speed of the motor is always close to the synchronous speed of the rotating flux.
- Since the synchronous speed is directly proportional to the frequency of the stator voltage, any change in frequency results in an equivalent change in motor speed.

$$n_s = 120\frac{f}{p}$$

- The effect of frequency on motor current is given

$$I'_2 = \frac{V}{\sqrt{\left(R_1 + \frac{R'_2}{s}\right)^2 + X_{eq}^2}}$$

- Frequency manipulation appears to be an effective method for speed control that requires a simple dc/ac converter with variable switching intervals.

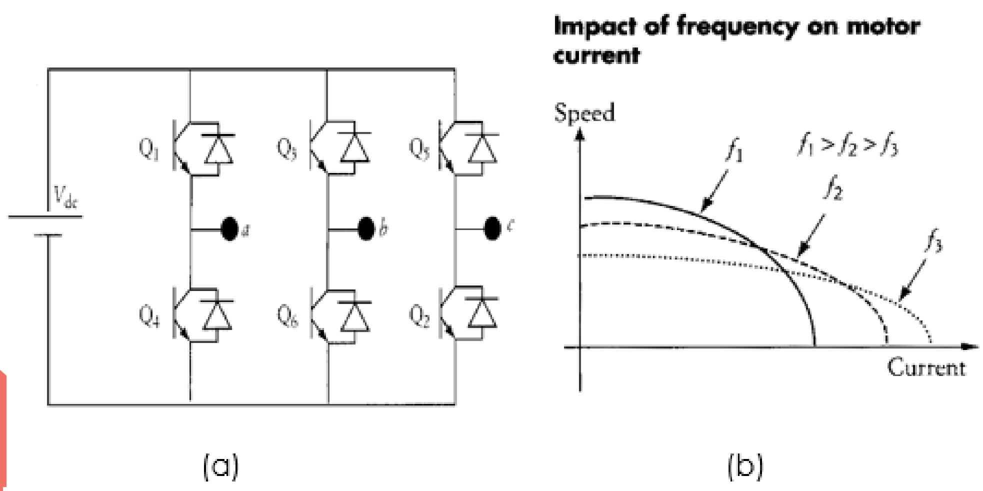
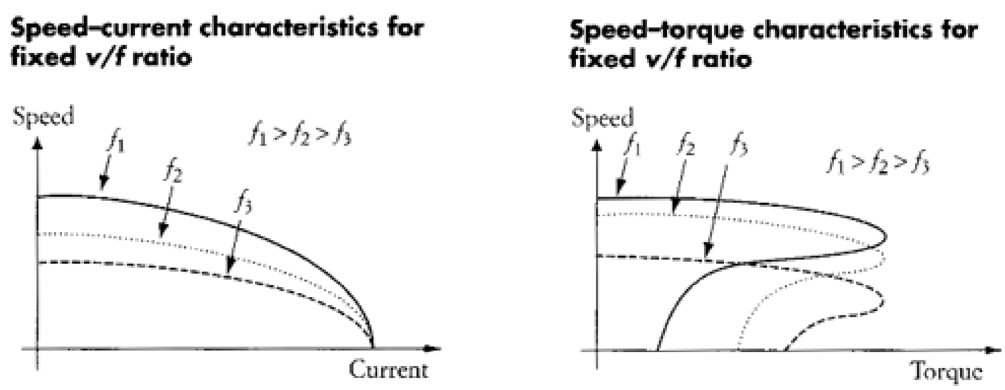



***Figure 4.5: (a) Inverter Circuit (b) Speed-Torque Characteristics – Impact of Voltage on Motor Speed***

# SPEED CONTROL OF AC MOTOR

## 4.7 CONTROLLING SPEED BY ADJUSTING THE VOLTAGE/FREQUENCY CONTROL

- The change in voltage and frequency is a powerful method for speed control. Refer Figure 3.6.
- Note that both frequency and voltage can change simultaneously by the pulse-width modulation technique.
- This type of control is common for induction motors. There are several variations where the v/f ratio is also adjusted to provide a special operating performance.
- The most common method, though, is the fixed v/f ratio.
- It is clear that when the v/f ratio is constant, the maximum torque is unchanged.




(a) (b)

*Figure 4.6: (a) Speed-Current Characteristics – Impact of Frequency Change on Motor Speed, (b) Speed-Torque Characteristics – Impact of Frequency Change on Motor Speed*

# SPEED CONTROL OF AC MOTOR

## 4.8 SLIP ENERGY RECOVERY (SER)

- Most of the input electric power $P_{in}$ is converted to mechanical power $P_{out}$ to support the load.
- However, part of $P_{in}$ is lost in the resistive element of the stator circuit $P_{cu1}$. Refer Figure 3.7.
- The rest is power transmitted to the rotor via the air gap $P_g$.
- At high speeds, most of $P_g$ is converted to mechanical developed power $P_d = (1-s)P_g$
- The rest is known as the slip power. Slip power is an electrical power dissipated in the rotor resistance in the form of rotor copper losses $P_{cu2}$.
- Slip power $P_s$, can be substantial at low speeds.

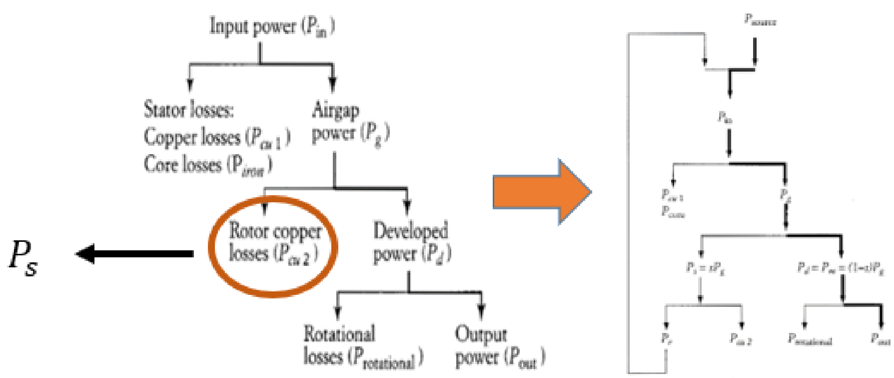



***Figure 4.7: Power Flow for Induction Motor – SER increase the efficiency***

- When a resistance in the rotor circuit is used to reduce the motor speed, the efficiency of the motor is substantially reduced.
- The speed reduction is due to the extra power dissipated in the rotor circuit, which results in less mechanical power for the load.
- We can still use this principle to reduce the motor speed, but instead of dissipating the extra power in the rotor resistance, we send it back to the source.
- This method is known as Slip Energy Recovery (SER) or Static Scherbius Drive.

# SPEED CONTROL OF AC MOTOR

## 4.8 SLIP ENERGY RECOVERY (SER)

- In the rotor resistance control method, the slip power in the rotor circuit is wasted as $I^2R$ losses during the low-speed operation.
- The efficiency is also reduced.
- The slip power from the rotor circuit can be recovered and fed back to the AC source to utilize it outside the motor.
- Thus, the overall efficiency of the drive system can be increased.
- SER recovered by adding variable voltage source in rotor of IM
- Variable source will absorb the slip power and send back to AC supply
- SER provide speed control of IM
- By varying magnitude of the variable voltage source → can control current, torque & slip of the rotor
- $I^2R$ losses decrease by control rotor resistance
- SER consist of 4 main components/block. Refer Figure 3.8.

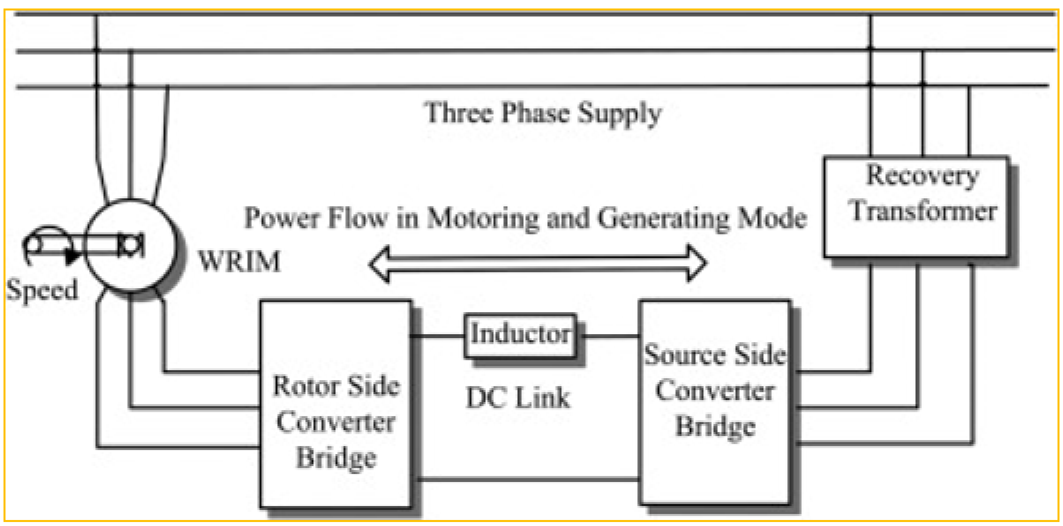



*Figure 4.8: Block Diagram for SER*

# SPEED CONTROL OF AC MOTOR

## 4.8 SLIP ENERGY RECOVERY (SER)

| | |
|---|---|
| **Rectifier** | • Connect to rotor. Convert AC → DC and force power flow away from winding |
| **Reactor** | • Smoothen the current |
| **Converter** | • Phase controlled → inversion mode convert DC → AC |
| **Transformer** | • Improve power factor. Power absorb by the rectifier send back to supply |

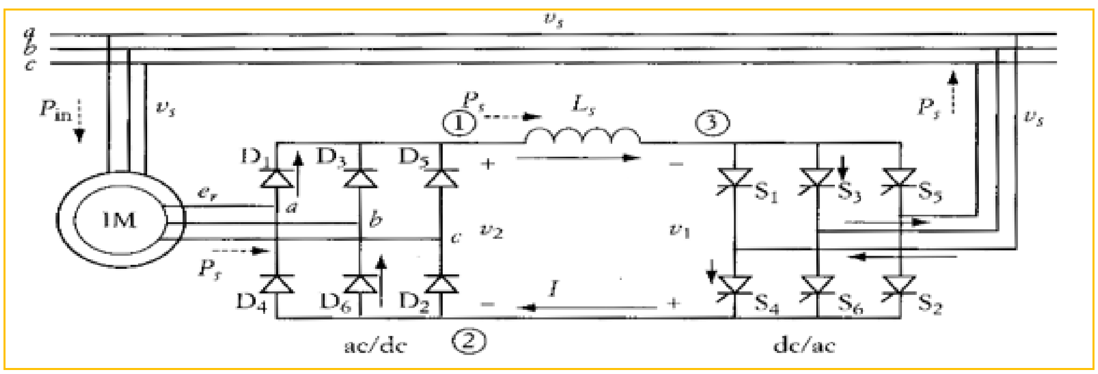



*Figure 4.9: Circuit Diagram for SER*

# SPEED CONTROL OF AC MOTOR

## 4.8 SLIP ENERGY RECOVERY (SER)

- The three-phase supply is a constant voltage source, $V_S$ is sinusoidal with fixed peak value. Hence, a change in the triggering angle of the SCRs changes the average value of $V_1$.
- Because the balance between $V_1$ and $V_2$ is always maintained in the loop of the dc link, $V_2$ must also change.
- When $V_2$ changes, the rotor voltage $e_r$ on the input side of the diode will change accordingly.
- $e_r$ is a function of the motor speed.

$$e_r = sE_2$$

- $e_r$ is a function of the motor speed and $E_2$ is the rotor voltage at standstill, which is constant. If we ignore the voltage drop of the stator windings, $E_2$ is constant when the stator voltage is maintained constant.
- And finally, the new speed for SER can be found as:

$$n = n_s\left[1 + \frac{N_1}{N_2}\cos(\alpha)\right]$$

- And the current of the motor:

$$I = \frac{T_d \omega_s}{KV_s}$$

- Where K is:

$$K = \frac{3\sqrt{2}}{\pi}\frac{N_2}{N_1}$$

# SPEED CONTROL OF AC MOTOR

## 4.8 SLIP ENERGY RECOVERY (SER)

- $V_s$ rms line-to-line voltage, $N_1$ and $N_2$ are the number of turns of the stator and rotor windings, respectively and $\alpha$ is the triggering angle of the dc/ac converter, measured from the zero crossing of the line-to-line voltage.
- It is shows that by adjusting the triggering angle of the dc/ac converter can control the speed of the machine.
- The range of α is from π/2 to π. In this range, the IM operates as a motor where the speed is less than the synchronous speed.
- With SER, the slip power is divided into the copper losses of the rotor and the recovery power $P_r$.
- The recovery power is injected back to the source.
- Thus, the actual power delivered by the source is the input power required by the motor minus $P_r$.

# SPEED CONTROL OF AC MOTOR

## 4.9 SUMMARY

**FORMULA FOR CHAPTER 3 (SUMMARY)**

$$Synchronous\ Speed, N_s = \frac{120f}{P}\ Where\ f = frequency\ \&\ P = No.of\ Poles$$

$$Motor\ Speed\ at\ full\ load, n = N_s(1-S)\ where\ S\ is\ Slip\ of\ the\ motor$$

$$Torque\ Developed, T_d = \frac{P_d}{\omega} = \frac{V^2 S}{\omega_S R'_2} = \frac{V^2 R'_2}{S\omega_S\left[\left(R_1 + \frac{R'_2}{S}\right)^2 + X_{eq}{}^2\right]}$$

Where,
V = Voltage Line-to-Line
S = Slip
$\omega_S$ =Synchronous Speed in rad/s
$R'_2$ = Rotor Resistance
$R_1$ = Stator Resistance
$P_d$= Power Developed
$X_{eq}$ = Reactance
$P_d$ = Power Developed

$$Power\ Developed, P_d = P_{out} + P_{rotational} = T_d\omega = \frac{V^2 S(1-S)}{R'_2} = 3(I'_2)^2\frac{R'_2}{S}(1-S)$$

$$P_{in} = P_d + P_{winding} + P_{core}$$

$$P_{winding} = P_{cu} + P_{cu2} = 3(I'_2)^2(R_1 + R'_2)$$

$$Motor\ efficiency, \eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$Slip, S = \frac{N_S - N_R}{N_S}$$

# SPEED CONTROL OF AC MOTOR

## 4.9 SUMMARY

$$Maximum\ Torque, T_{max} = \frac{V^2}{2\omega_s(R_1 + \sqrt{{R_1}^2 + {X_{eq}}^2})} = \frac{V^2}{2(\frac{f}{60}\omega_s)(\frac{f}{60}X_{eq})}$$

$$Motor\ Starting\ Current, I'_{2st} = \frac{V}{\sqrt{(R_1 + R'_2)^2 + {X_{eq}}^2}}$$

$$Starting\ Torque, T_{st} = \frac{3(I'_{2st})^2 R'_2}{\omega_s}$$

$$Motor\ Current, I'_2 = \frac{V}{\sqrt{\left(R_1 + \frac{R'_2}{S}\right)^2 + {X_{eq}}^2}}$$

$$Rotor\ Voltage\ (SER), e_r = sE_2$$

$$Rotor\ voltage\ at\ standstill, E_2 = \frac{N_2}{N_1}(V_S)$$

$$Maximum\ Slip, S_{max} = \frac{R'_2}{\sqrt{{R_1}^2 + {X_{eq}}^2}}$$

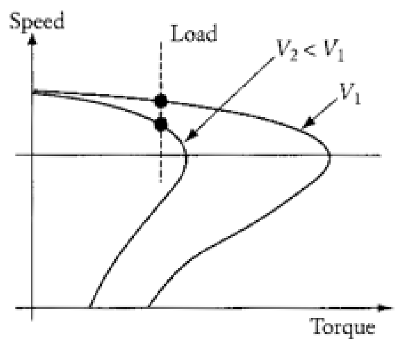
# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

**Example 4.1:**

(a) Discuss the effect of the speed control by adjusting stator voltage method on AC motor speed with the aid of speed-torque curve.
Solution:

**Impact of voltage on motor speed**



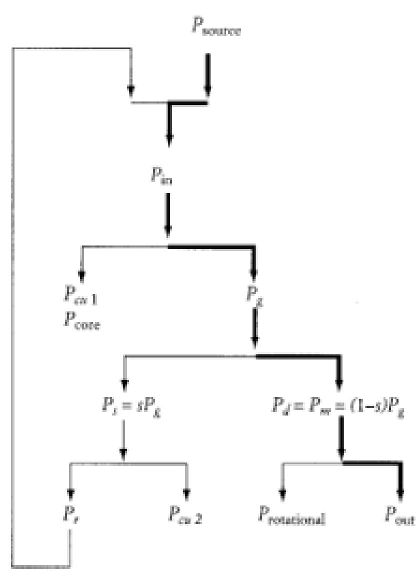

- By vary supplying voltage, speed can be controlled. The voltage is varied until the torque required by the load is developed at the desired speed. The torque developed is proportional to the square of the supply voltage and the slip at maximum torque is independent of the supply voltage (torque remains unchanged).
- Motor speed change when the voltage is altered
- Starting current reduced since it is directly proportional to the stator voltage.
- While losses are reduced (core losses proportional to the square of the voltage)
- Synchronous speed directly proportional to the frequency of the stator voltage, any change in frequency will change in motor speed.

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

(b) For the principle of SER, draw the power flow chart of IM under energy recovery

**Power flow chart of induction motor under energy recovery**



# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

**Example 4.2:**

A 480V, 2-pole, 60Hz, Y connected IM has an inductive reactance of 4Ω and a stator resistance of 0.2Ω. The rotor resistance referred to the stator is 0.3Ω. The motor is driving a constant-torque load of 60Nm at a speed of 3500 rpm. Assume that this torque includes to rotational components.

i) Compute the maximum frequency of the supply voltage that would not result in starting the motor
ii) Calculate the motor current at 60Hz and at the maximum frequency
iii) Calculate the power delivered to the load at 60Hz and at the maximum frequency
iv) Compute the motor speed and starting current if the frequency is decreased to 50Hz

Solution:

i) Maximum frequency of the supply voltage

Step 1: Calculate synchronous speed of the motor in rpm & rad/sec

$$Ns = \frac{120f}{P} = \frac{120(60)}{2} = 3600rpm$$

$$\omega_s = \frac{2\pi}{60} \mathrm{N}_s = \frac{2\pi}{60} 3600\ rad/sec$$

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

Step 2: Calculate frequency from Torque Developed ($T_d$) formula

$$T_{max} = \frac{V}{2\omega_s(R_1 + \sqrt{{R_1}^2 + {X_{eq}}^2})} = \frac{V^2}{2(\frac{f}{60}\omega_s)(\frac{f}{60}X_{eq})}$$

$$T_{max} = T_d = 60nm = \frac{480^2}{2(\frac{f}{60}2\pi\frac{3600}{60})(\frac{f}{60}4)}$$

$$\therefore f = \mathbf{67.7Hz}$$

Note: The increase in frequency should not exceed 67.7Hz

ii) Motor Current

Step 1: Calculate Slip, S

$$At\ 60Hz, S = \frac{n_s - n_r}{n_s} = \frac{3600 - 3500}{3600} = 0.0277$$

Step 2: Calculate motor current, $I'_2$

$$I'_2 = \frac{V}{\sqrt{\left(R_1 + \frac{R'_2}{S}\right)^2 + {X_{eq}}^2}}$$

$$I'_2 = \frac{\frac{480}{\sqrt{3}}}{\sqrt{\left(0.2 + \frac{0.3}{0.0277}\right)^2 + 4^2}} = 23.62A$$

Step 3: Calculate new equivalent reactance, $X_{eq}$ at maximum frequency, f = 67.7Hz

$$X_{eq} = \frac{f_{new}}{f_{old}}\left(X_{eqold}\right) = \frac{67.7}{60}(4) = 4.51$$

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

Step 4: Calculate new maximum Slip, $S_{max}$

$$S_{max} = \frac{R'_2}{\sqrt{R_1{}^2 + Xeq^2}} = \frac{0.3}{\sqrt{0.2^2+4.51^2}} = 0.0665$$

Step 5: Calculate new speed

$$N_s = \frac{120f}{P}(1 - S_{max}) = 120\left(\frac{67.7}{2}\right)(1 - 0.0665) = 3792rpm$$

Step 6: Calculate the current at the new frequency

$$I'_2 = \frac{\frac{480}{\sqrt{3}}}{\sqrt{(0.2 + \frac{0.3}{0.0665})^2 + 4.51^2}} = \mathbf{42.5A}$$

iii) The developed power at 60Hz is

$$P_d = T_d\omega = 60 \times 2\pi \times \frac{3500}{60} = 22kW$$

At 67.7Hz,

$$P_d = T_d\omega = 60 \times 2\pi \times \frac{3792}{60} = 23.83kW$$

The increase of power developed is about 8.3%

iv) New Synchronous Speed, $Ns_{new}$ and Starting Current if the frequency is decreased to 50Hz

Step 1: Calculate new speed when f=50Hz

$$Ns = \frac{120f}{P}(1 - S_{max}) = 120\left(\frac{67.7}{2}\right)(1 - 0.0665) = 3792rpm$$

$$Ns = \frac{120(50)}{2} = 3000rpm$$

In rad/sec

$$\omega_s = \frac{2\pi}{60}N_s = \frac{2\pi}{60}3000 = 314.16\ rad/sec$$

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

Step 2: Calculate new slip, S from Torque Developed, $T_d$

$$T_d = \frac{V^2 S}{\omega_S R'_S}$$

$$60 = \frac{480^2 S}{314.16(0.3)}$$

$$\therefore S = 0.0245$$

Step 3: Calculate new speed when consider slip (at full load)

$$Ns = 3000(1 - 0.0245) = 2926.5rpm\ (increase\ 19\%)$$

Step 4: Calculate motor starting current, $I'_2$

$$I'_{2st} = \frac{V}{\sqrt{(R_1 + R'_2)^2 + {X_{eq}}^2}}$$

At 60Hz

$$I'_{2st} = \frac{\frac{480}{\sqrt{3}}}{\sqrt{0.5^2 + 4^2}} = 68.75A$$

At 50Hz

$$I'_{2st} = \frac{\frac{480}{\sqrt{3}}}{\sqrt{0.5^2 + (\frac{50}{60}4^2)}} = 82.21A$$

Note: 20% increase in the starting current. Note, if f decrease, Ns decrease and Starting Currents, $I'_{2st}$ will increase.

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

**Example 4.3:**

A 209V, three phase, six-pole, Y-connected induction motor has the following parameters:

$R_1 = 0.128\Omega$ $R'_2 = 0.0935\Omega$ $X_{eq} = 0.49\Omega$

The motor slip at full load is 2%. Calculate the following:

a. Starting current (ignore the magnetizing current)
b. Full load current
c. Starting Torque
d. Maximum torque
e. Motor Efficiency (ignore rotational and core losses)

Solution:

a) Motor starting current, $I'_{2st}$

$$I'_{2st} = \frac{V}{\sqrt{(R_1 + R'_2)^2 + {X_{eq}}^2}}$$

$$I'_{2st} = \frac{\frac{209}{\sqrt{3}}}{\sqrt{(0.128 + 0.0935)^2 + 0.49^2}} = 224.46A$$

b) Motor current, $I'_2$ at full load

$$I'_2 = \frac{V}{\sqrt{\left(R_1 + \frac{R'_2}{S}\right)^2 + {X_{eq}}^2}}$$

$$I'_2 = \frac{\frac{209}{\sqrt{3}}}{\sqrt{(0.128 + \frac{0.0935}{0.02})^2 + 0.49^2}} = \mathbf{25A}$$

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

c) Starting Torque, $T_{st}$

Step 1: Calculate synchronous speed of the motor in rpm & rad/sec. Assume f=60Hz

$$Ns = \frac{120f}{P} = \frac{120(60)}{6} = 1200rpm$$

$$\omega_s = \frac{2\pi}{60}\mathrm{N}_s = \frac{2\pi}{60}1200 = 125.66rad/sec$$

Step 2: Calculate $T_{st}$

$$T_{st} = \frac{3(I'_{2st})^2 R'_2}{\omega_s} = \frac{3(224.46)^2(0.0935)}{125.66} = 112.46Nm$$

d) Maximum Torque, $T_{max}$

$$T_{max} = \frac{V^2}{2\omega_s(R1 + \sqrt{{R_1}^2 + {X_{eq}}^2})} = \frac{209^2}{2(125.66)(0.128 + \sqrt{(0.128^2 + 0.49^2)})}$$
$$= 273.95Nm$$

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

e) Motor Efficiency, η

Step 1: Calculate Power Developed, $T_d$

$$P_d = \frac{V^2 S(1-S)}{R'_2} = \frac{209^2(0.02)(1-0.02)}{0.0935} = 9157W$$

Step 2: Calculate Losses, $P_{winding}$

$$P_{winding} = 3(I'_2)^2(R_1 + R'_2) = 3(25)^2(0.128 + 0.0935) = 415.3W$$

Step 3: Calculate Input Power, $P_{in}$

$$P_{in} = P_d + P_{winding} = 9157 + 415.3 = 9572.3W$$

Step 4: Calculate Output Power, $P_{out}$

$$P_{out} = P_d + P_{rotational} = 9157 + 0 = 9157W$$

Step 5: Calculate motor efficiency, η

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{9157}{9572.3} \times 100\% = 96\%$$

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

**Example 4.4:**

A three-phase, 480V, six-pole, Y-connected, 60Hz, 10kW, 1150rpm induction motor is driving a constant-torque load of 60Nm. The parameters of the motor are:

$R_1=0.4\Omega$ $R'_2= 0.5\Omega$ $X_{eq}= 4\Omega$ $\frac{N_1}{N_2} = 2$

Calculate the following:

a. Motor torque
b. Motor current
c. Starting Torque
d. Starting Current

Solution:

a) Motor Torque, T

Step 1: Calculate synchronous speed of the motor in rpm & rad/sec

$$Ns = \frac{120f}{P} = \frac{120(60)}{6} = 1200rpm$$

$$\omega_s = \frac{2\pi}{60}\mathrm{N}_s = \frac{2\pi}{60}1200 = 125.66\ rad/sec$$

Step 2: Calculate Motor Torque Developed($T_d$)

$$T_{max} = \frac{V}{2\omega_s(R_1 + \sqrt{{R_1}^2 + {X_{eq}}^2})} = \frac{V^2}{2(\frac{f}{60}\omega_s)(\frac{f}{60}X_{eq})}$$

$$T_{max} = T_d = \frac{480^2}{2(\frac{60}{60}125.66)(\frac{60}{60}4)}$$

$$\therefore T_d = \mathbf{229.19Nm}$$

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

b) Motor Current, $I'_2$

Step 1: Calculate Slip, S

$$At\ 60Hz, S = \frac{n_s - n_r}{n_s} = \frac{1200 - 1150}{1200} = 0.0417$$

Step 2: Calculate motor current, I'2

$$I'_2 = \frac{V}{\sqrt{\left(R_1 + \frac{R'_2}{S}\right)^2 + {X_{eq}}^2}}$$

$$I'_2 = \frac{\frac{480}{\sqrt{3}}}{\sqrt{\left(0.4 + \frac{0.5}{0.0417}\right)^2 + 4^2}} = 21.28A$$

c) Starting Torque, $T_{st}$

Step 1: Calculate Motor Starting Current, $I'_{2st}$

$$I'_{2st} = \frac{V}{\sqrt{(R_1 + R'_2)^2 + {X_{eq}}^2}}$$

$$I'_{2st} = \frac{\frac{480}{\sqrt{3}}}{\sqrt{(0.4 + 0.5)^2 + 4^2}} = 67.59A$$

Step 2: Calculate $T_{st}$

$$T_{st} = \frac{3(I'_{2st})^2 R'_2}{\omega_s} = \frac{3(67.59)^2(0.5)}{125.66} = 54.53Nm$$

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

**Example 4.5:**

A 480V, three phase, 60Hz, six-pole, Y-connected induction motor has the following parameters:

$R_1$=0.2Ω $R'_2$= 0.1Ω $X_{eq}$= 5Ω

The load of the motor is a drilling machine. At 1150 rpm, the load torque is 150Nm. The motor is driven by a constant v/f technique. When the frequency of the supply voltage is reduced to 50Hz, calculate the following:

a. Motor speed

b. Maximum torque at 60Hz and 50Hz

c. Motor current at 50Hz

Solution:

a) Motor Speed, Ns

Step 1: Calculate synchronous speed of the motor in rpm & rad/sec

For f = 60Hz

$$Ns = \frac{120f}{P} = \frac{120(60)}{6} = 1200rpm$$

$$\omega_s = \frac{2\pi}{60}\mathrm{N}_s = \frac{2\pi}{60}1200 = 125.66\, rad/sec$$

For f = 50Hz

$$Ns = \frac{120f}{P} = \frac{120(50)}{6} = 1000rpm$$

$$\omega_s = \frac{2\pi}{60}\mathrm{N}_s = \frac{2\pi}{60}1000 = 104.72\, rad/sec$$

# SPEED CONTROL OF AC MOTOR

## 4.9 CALCULATION EXAMPLE

b) Maximum torque, $T_{max}$

Step 1: Calculate Motor Torque Developed ($T_d$) for f = 60Hz

$$T_{max} = \frac{V^2}{2\omega_s(R_1 + \sqrt{{R_1}^2 + {X_{eq}}^2})} = \frac{V^2}{2(\frac{f}{60}\omega_s)(\frac{f}{60}X_{eq})}$$

$$T_{max} = T_d = \frac{480^2}{2(\frac{60}{60}125.66)(\frac{60}{60}5)}$$

$$\therefore T_d = \mathbf{183.35Nm}$$

Step 2: Calculate Motor Torque Developed ($T_d$) for f = 50Hz

$$T_{max} = \frac{V}{2\omega_s(R_1 + \sqrt{{R_1}^2 + {X_{eq}}^2})} = \frac{V^2}{2(\frac{f}{60}\omega_s)(\frac{f}{60}X_{eq})}$$

$$T_{max} = T_d = \frac{480^2}{2(\frac{50}{60}104.72)(\frac{50}{60}5)}$$

$$\therefore T_d = \mathbf{316.82Nm}$$

c) Motor Current at 50Hz

Step 1: Calculate Slip, S

$$At\ 50Hz, S = \frac{n_s - n_r}{n_s} = \frac{1150 - 1000}{1150} = 0.13$$

Step 2: Calculate motor current, $I'_2$

$$I'_2 = \frac{V}{\sqrt{\left(R_1 + \frac{R'_2}{S}\right)^2 + {X_{eq}}^2}}$$

$$I'_2 = \frac{\frac{480}{\sqrt{3}}}{\sqrt{\left(0.2 + \frac{0.1}{0.13}\right)^2 + 5^2}} = \mathbf{54.57A}$$

# SPEED CONTROL OF AC MOTOR

## 4.10 REVIEW QUESTION

1. Identify THREE (3) methods of speed control for Induction Motor
2. State THREE (3) advantages of AC Motor
3. Explain the effect for v/f technique in controlling the speed of AC Induction Motor.
4. Sketch and label the circuit of Slip Energy Recovery (SER).
5. Explain the block diagram of SER.

# SPEED CONTROL OF AC MOTOR

## 4.11 CALCULATION QUESTIONS

1. A 209V, three phase, six-pole, Y-connected induction motor has the following parameters:

$R_1$=0.251Ω    $R'_2$= 0.0911Ω    $X_{eq}$= 0.53Ω

The motor slip at full load is 1%. Calculate the following:

a. Starting current (ignore the magnetizing current)
b. Full load current
c. Starting Torque
d. Maximum torque
e. Motor Efficiency (ignore rotational and core losses)

2. A three-phase, 480V, six-pole, Y-connected, 60Hz, 10kW, 1150rpm induction motor is driving a constant-torque load of 60Nm. The parameters of the motor are:

$R_1$=0.8Ω    $R'_2$= 0.5Ω    $X_{eq}$= 6Ω    $\frac{N_1}{N_2} = 3$

Calculate the following:

a. Motor torque
b. Motor current
c. Starting Torque
d. Starting Current

# SPEED CONTROL OF AC MOTOR

## 4.11 CALCULATION QUESTIONS

3. A 480V, three phase, 60Hz, six-pole, Y-connected induction motor has the following parameters:

$R_1$=0.4Ω   $R'_2$= 0.2Ω   $X_{eq}$= 5Ω

The load of the motor is a drilling machine. At 1200 rpm, the load torque is 200Nm. The motor is driven by a constant v/f technique. When the frequency of the supply voltage is reduced to 40Hz, calculate the following:

a. Motor speed

b. Maximum torque at 60Hz and 40Hz

c. Motor current at 40Hz

4. A three-phase, four pole, Y-connected, 480V induction motor is driving a 400Nm constant-torque load. The motor has the following parameter

$P_{rotational}$ =1kW   $\frac{N_1}{N_2} = 1$

The motor is driven by a Slip-Energy-Recovery system. The triggering angle of the dc/ac converter is adjusted to 120°. Calculate the following:

a. Motor Speed

b. Current in dc link

c. Rotor rms current

d. Stator rms current

e. Power returned back to the source

5. A three-phase, 60Hz, Y-connected, 480V induction motor rotates at 3500rpm at full load. The motor is driven by a Slip-Energy-Recovery system. Calculate the triggering angle for a motor speed of 2800rpm. Assume the turns ratio is equal to 1.

# SUMMARY OF CHAPTER

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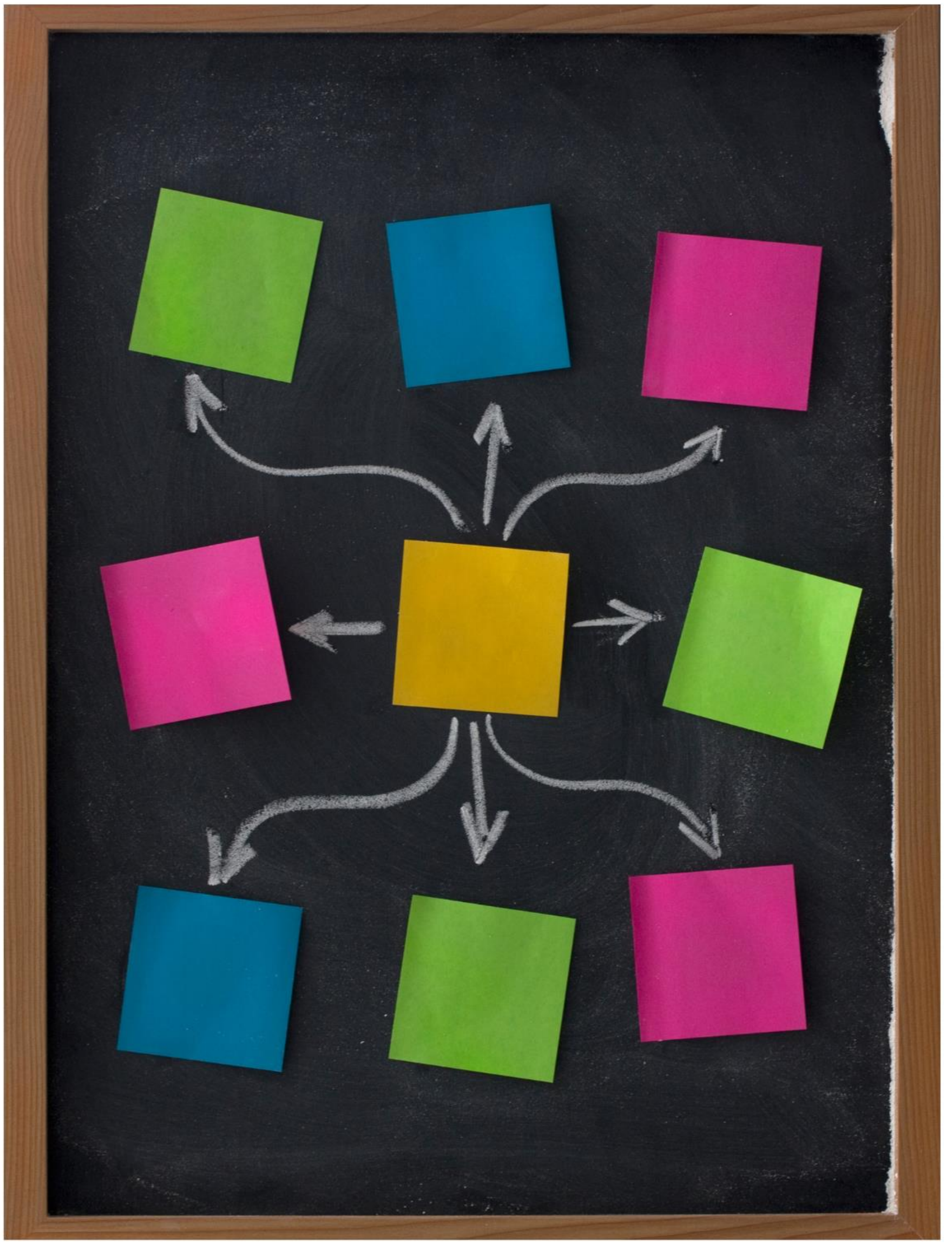

# MOTOR CONTROL & DRIVES

**MOTOR CONTROL & DRIVES** is written based on Malaysia Polytechnic Syllabus as a reference text for diploma students in electrical engineering. The book (Part 1) covers four chapters comprising the fundamentals of motor control, introduction to electrical drives, speed control of DC motor and AC motor. The chapters discuss the fundamental concepts and operating principles for motor control and drives.

**KEY FEATURES**

- Complies with syllabus of the Motor Control & Drives courses in Malaysia Polytechnics
- Clear and concise explanation of all the important principles, supported by figure, tables and formula.
- Examples with worked solutions
- Review questions at the end of each chapter, with answers provided in part 2 e-book.
- A summary blank notes that student can used to do quick revision of important concepts and principles with their own.

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