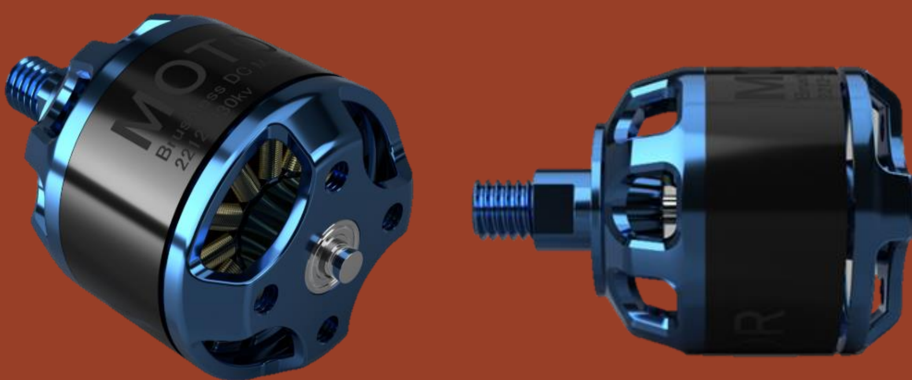
POLITEKNIK MALAYSIA
PORT DICKSON

DET50063 MOTOR CONTROL AND DRIVES

BRAKING OF DC & AC MOTOR



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POLITEKNIK MALAYSIA
PORT DICKSON

DET50063
MOTOR CONTROL AND DRIVES :

BRAKING OF DC & AC MOTOR

ACKNOWLEDGEMENT

[MOTOR CONTROL & DRIVES : BRAKING OF DC & AC MOTOR]

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We would like to convey our utmost gratitude to the Department of Polytechnic and Community College Education particularly the E-learning and Instructional Division (BIPD) for funding our e-book project.

We hereby declare that this module is our original work. To the best of our knowledge it contains no materials previously written or published by another person. However, if there is any, due acknowledgement and credit are mentioned accordingly in the e-book.

PUBLICATION DETAIL

[MOTOR CONTROL & DRIVES : BRAKING OF DC & AC MOTOR]

Cataloguing Information (to be informed)

PUBLISHED BY:

Politeknik Port Dickson

KM14, Jalan Pantai, 71050 Si Rusa

Port Dickson, Negeri Sembilan

AUGUST 2021

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ISBN
BARCODE

PREFACE

[MOTOR CONTROL & DRIVES : BRAKING OF D & AC MOTOR]

Motor Control & Drives e-Book is intended for non-specialist users of electric motor control and drives, filling the gap between mathematical formulas and theory-based academic textbook, which provide useful knowledge for understanding braking of DC & AC motor. The e-Book explores the methods braking for DC and AC motor.

This e-Book is designed in accordance with the course content of DET50063 Motor Control and Drives based on the local polytechnic syllabus for students of the Department of Electrical Engineering. Hopefully this e-book would be advantageous as a teaching text for a one semester course on the fundamentals of Motor Control and Drives. Students are expected to be familiar with the basic circuit theories and the knowledge of the principal operations and applications of motor control and electrical drives in braking of DC and AC motors.

We hereby declare that all contents are solely written by us, and all sources has been written as our book references.

ABSTRACT

[MOTOR CONTROL & DRIVES : BRAKING OF DC & AC MOTOR]

DET50063 MOTOR CONTROL AND DRIVES provide student with the knowledge of the principle operations and applications of motor control and electrical drives. This e-book covers the methods braking for DC and AC motors. Emphasis is given on principle operation, characteristic curve and solving the related problems. Various control methods based on the concept and principle of motor control and drives is showed by considering energy efficiency and also appropriate electrical equipment.

We hope that this e-book will benefit all students in DET50063 Motor Control and Drives topic.

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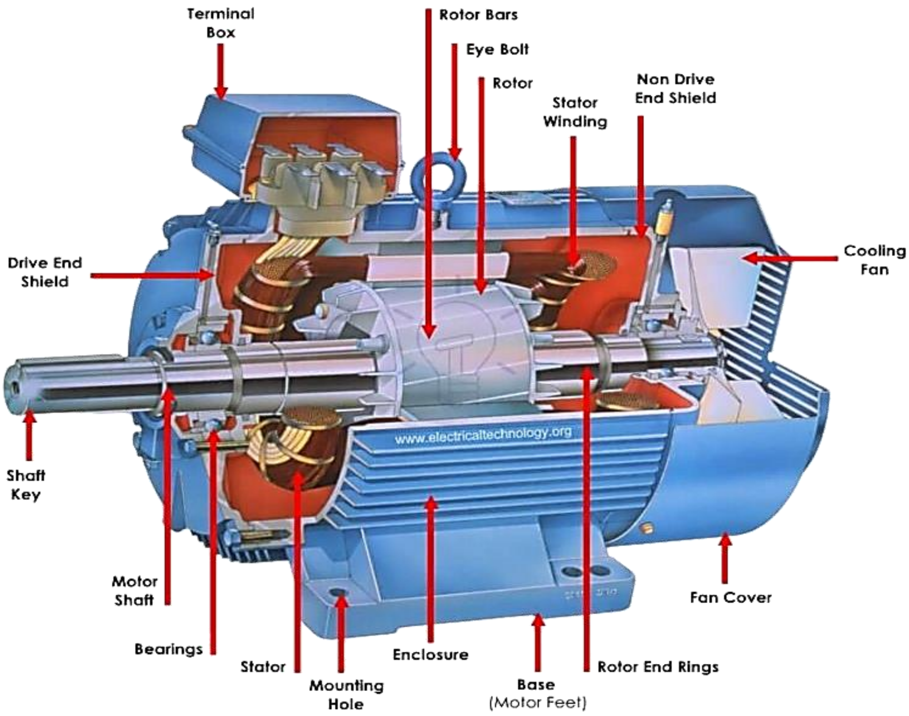
T O P I C 1

INTRODUCTION TO ELECTRICAL DRIVES

Upon completion of this subtopic, students should be able to:

- Recognize the block diagram of an electrical drive system.
- Describe the function of the components in electrical drive system
- Recognize the speed–torque characteristic for dc and ac motor
- Understand and analyze the concept of four quadrants in motor

DID YOU KNOW ?



(Source :Electricaltechnology.org,2020)

"A **motor** is the **mechanical or electrical device** that **generates** the **rotational or linear force** used to power a machine. A **drive** is the **electronic device that harnesses and controls the electrical energy** sent to the motor"

Drive feeds electricity into the motor in certain amount and frequency hence indirectly controlling the motor's speed and torque.

(Source: machinedesign.com)

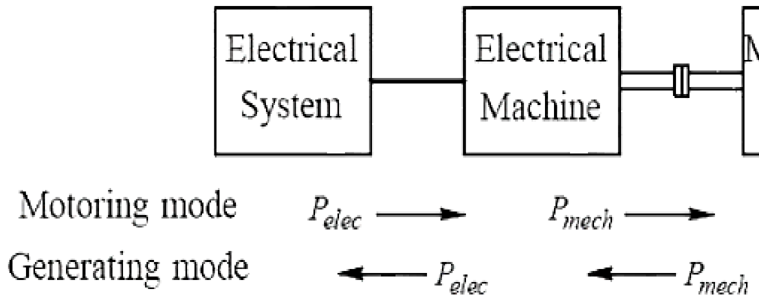
The combination of a motor and a drive will form a "drive system".

TOPIC 1 – INTRODUCTION TO ELECTRICAL DRIVES

1.1 Define An Electrical Driver

Electric drive – combination of several machine equipment that form to convert electric energy into mechanical energy. This process will control the electrical or electronical process in that equipment.

Essentially, an electrical driver controls the motor protection and monitoring functions, the direction, speed, and torque of an electric motor. Electrical drives, to put it plainly, are "the system that controls the motion of electrical machines."



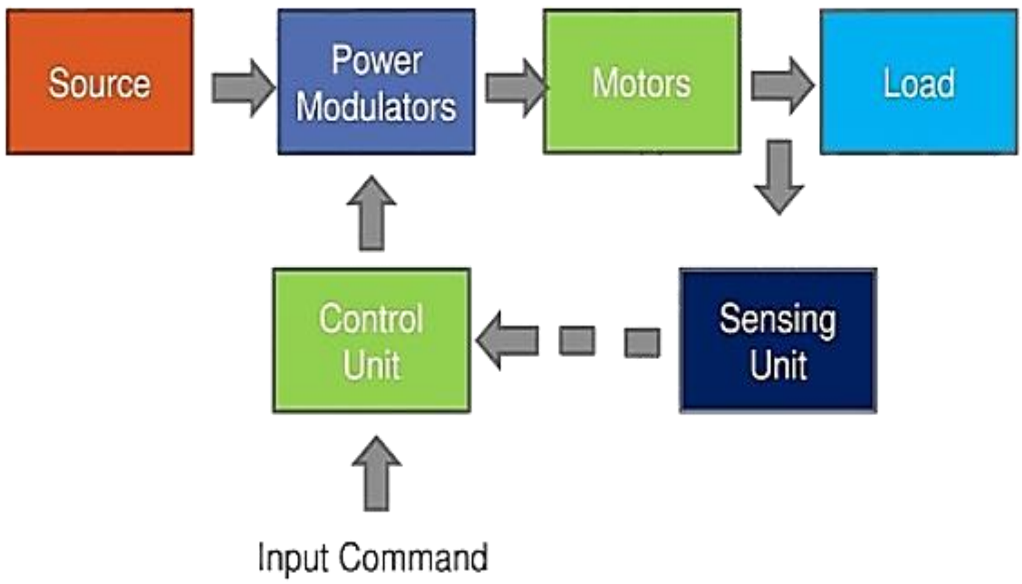


Figure 1.1 – Elements of an electric drive system
(Sources: El-Sharkawi, 2018)

1.2 Advantages Of An Electrical Driver

Advantages of electrical drives :

- The control characteristics can be manipulated as per requirements.
- Availability of simple and easy speed control methods.
- Electric braking can be employed in easy manner.
- The operation is pollution free.
- Wide range of speed, power and torque ratings are available.
- Higher efficiency as no load losses.
- Self-starting, without requirement of any starting equipment.
- Able to operate in all the four quadrants of speed torque plane
- The systems can be started instantly and can be loaded immediately without refuelling or preheating

TOPIC 1 – INTRODUCTION TO ELECTRICAL DRIVES

1.3 Block Diagram Of An Electrical Driver

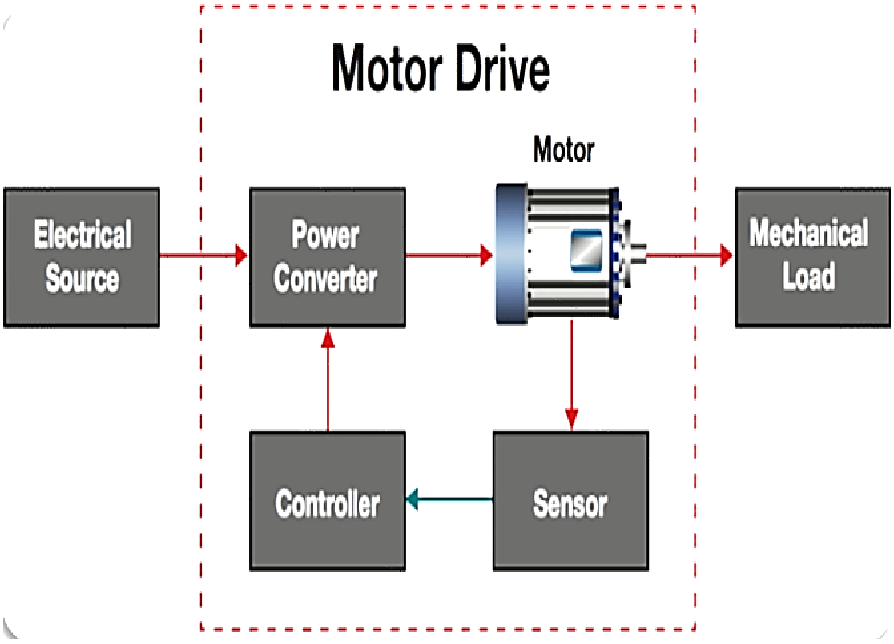


Figure 1.2 – Block diagram of an electrical driver
(*Sources: El-Sharkawi, 2018)*

1.4 Components In Electrical Drive System

The main components of the electric drive are :

- Power converter / modular
- Motor
- Control unit
- Sensing unit

Power converter :

The converter interfaces the motor with the power source and provides the motor with adjustable voltage, current and frequency. It converts electrical energy of the source in the form of suitable to the motor. During transient period such as starting, braking and speed reversal, it restricts source and motor current within permissible limits.

1.4 Components In Electrical Drive System

Types of Power Converter :

- Controlled rectifiers (AC to DC converters)
- Inverters (DC to AC converters)
- AC voltage controllers (AC to AC converters)
- DC choppers (DC to DC converters)
- Cyclo converters (Frequency conversion)

Motor :

They convert the energy from electrical to mechanical, so they can be considered as energy converters. Most commonly used motors for speed control applications are DC motors and AC motors. The choice of the type of use depends on the application and the available sources.

Control Unit

The control unit operates the power converters as required. The motor and power converter are matched to fulfil the load requirements. It inputs the command signal, from the input to the control unit, adjust the working point of the driver.

Sensing Unit

It senses certain drive parameters, such as motor current and speed. From motor it senses speed, torque, position, current and voltage from electric motor terminals. From load it senses torque and temperature.

Source

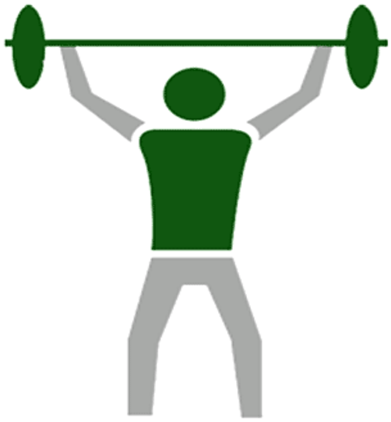
AC and DC are the two types of power sources for electrical drives. AC sources are single phase or three phase AC supplies.

Mechanical Load

The motor shaft is coupled with the mechanical load, which is commonly referred to as machinery, such as flow rates in pumps, fans, robots, machine tools, trains, and drills.

DID YOU KNOW

HORSEPOWER (Speed) vs TORQUE (Strength)



The power produced by an engine is called its **horsepower**. In physics, power is defined as the rate at which something does work.

For cars, horsepower translates into speed. So, if you want to go faster and get up to speed quicker, you need more horsepower.

Torque, on the other hand, is the expression of a rotational or twisting force. In vehicles, the engines rotate around an axis, thus creating torque.

Torque can be viewed as the "strength" of a vehicle. It's the force that rockets a sports car from 0-60 in seconds and pushes you back in the seat. It's also what powers big trucks hauling heavy loads into motion.

(Source : Bryantmotors)

1.5 Speed-torque Characteristics Of DC Motor

Habib (2019) stated that the speed-torque characteristics determined a performance of a DC motor. Those characteristics are :

- Torque – armature current characteristics
- Speed – armature current characteristics
- Speed-torque characteristics

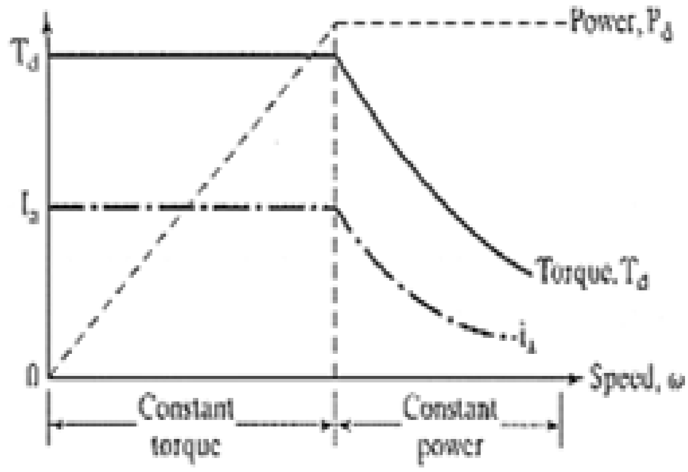


Figure 1.3 – Speed-torque characteristic curve of DC motor
(Sources: El-Sharkawi, 2018)

For a speed up to the base speed, the armature voltage is varied, and the torque is maintained constant. The speed-torque connection follows the natural characteristic of the motor after the rated armature voltage is applied, 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.

1.6 Speed-torque Characteristics Of AC Motor

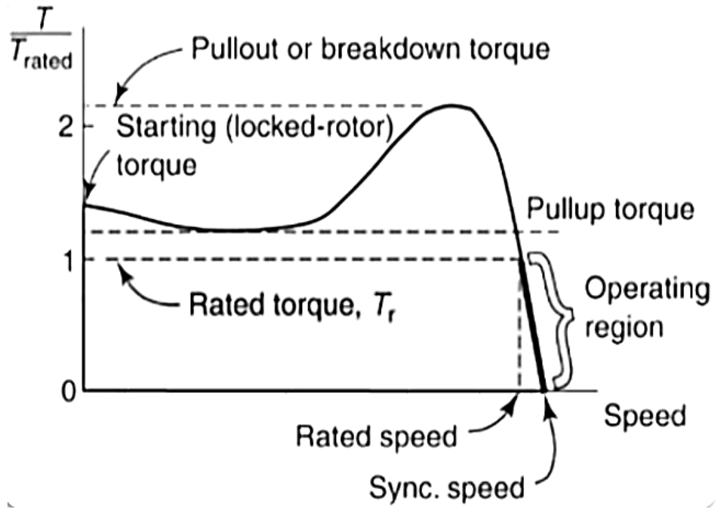


Figure 1.4 – Speed-torque characteristic curve of AC motor
(Sources: El-Sharkawi, 2018)

1) Locked Rotor Torque Or Starting Torque

The locked rotor torque or starting torque is the torque the electrical motor develop when it starts at rest or zero speed. It needs a high torque to start and rotate the motor from a the standstill condition to a rotating condition. As high torque is obtained, starting current is generated to develop the high starting torque.

2) 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.

3) Break-down Torque

The break-down torque is the highest torque available before the torque decreases when the machine continues to accelerate in the operating conditions.

1.7 Four Quadrant In Motor Operation

Four quadrant operation of any motor means that the machine operates in four quadrants. They are :

- Forward braking
- Forward motoring
- Reverse motoring
- Reverse braking

A motor operates in two (2) modes – **motoring and braking :**

- In **motoring mode** : The machine works as a motor and converts the electrical energy into mechanical energy, supporting its motion.
- In **braking mode** : The machine works as a generator and converts mechanical energy into electrical energy and as a result, it opposes the motion.

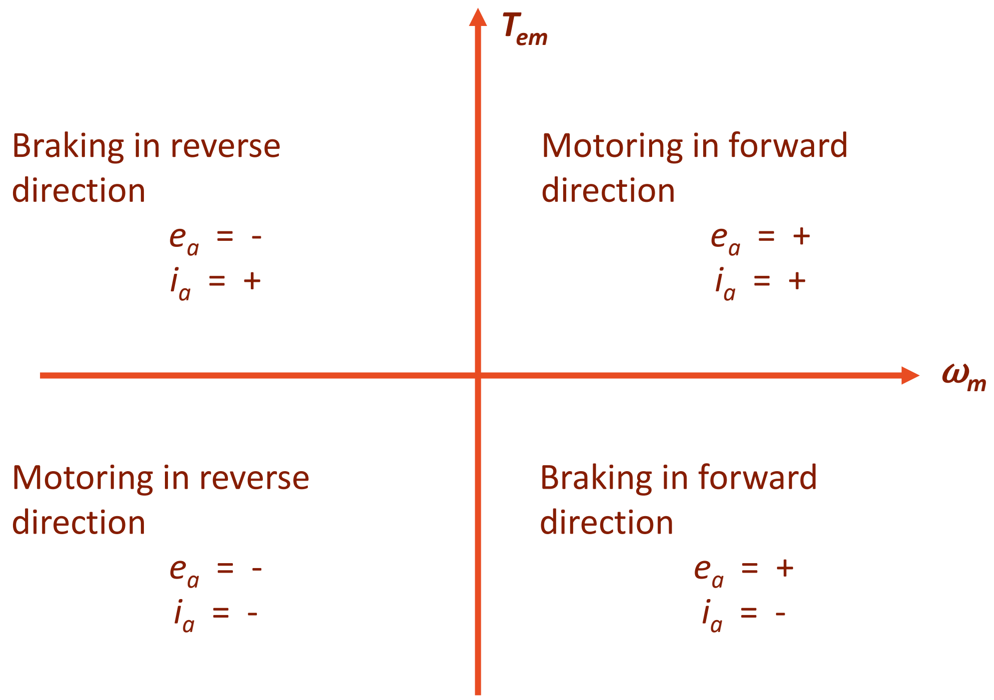


Figure 1.5 – Four-quadrant in motor operation
(Sources: John Wiley & Sons, 2003)

1.8 Four Quadrant Operation In DC Motor

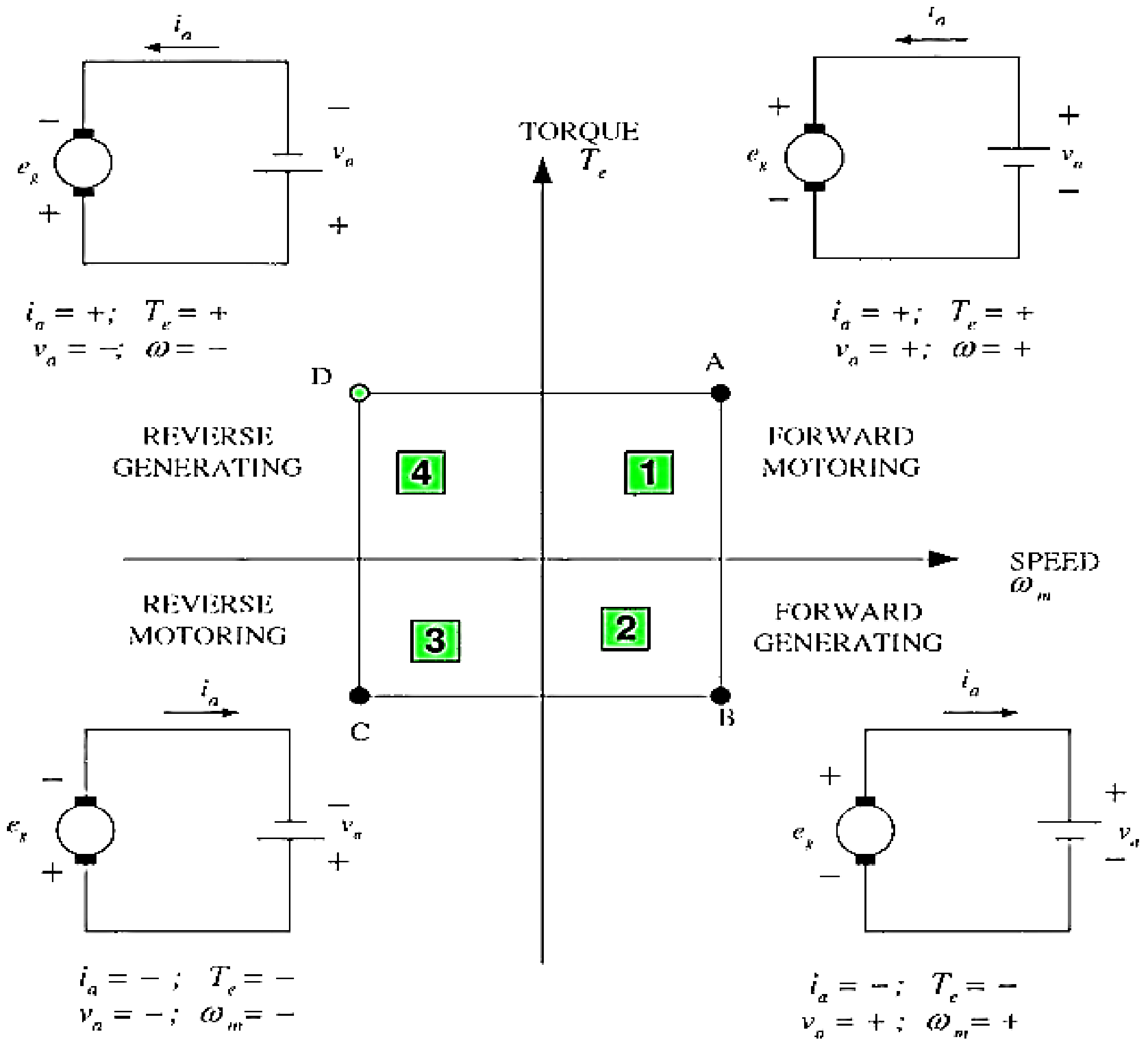


Figure 1.6 – The torque and speed co-ordination for forward and reverse motions
(Sources: El-Sharkawi, 2018)

1.8 Four Quadrant Operation In DC Motor

Quadrant 1

The torque and speed are in forward direction motions. The developed power is positive, hence machine works as a motor supplying mechanical energy. Therefore, the first quadrant operation is called **forward motoring.**

Quadrant 2

In this quadrant, the direction of the speed is forward but the motor torque is in the opposite direction or negative value. The torque produced by the motor is used to oppose the motion of the rotating motor. The product of the torque and speed is negative. Thus, the power is negative, implying that the motor operates in braking mode. The mode of operation is known as **forward braking** or as a **forward generating**.

Quadrant 3

The speed and torque of the motor are in the same direction, but both are negative. The reverse electrical torque is used to rotate the motor in reversed direction. The product of the torque and speed is positive implying that the motor operates in motoring mode. The energy is converting from electrical form to mechanical form. The term for this operation mode known as **reverse motoring**.

Quadrant 4

The speed is in reversed direction, but the motor torque is in opposite. The torque is used to brake the reversed rotating of the motor. The product of the torque and speed is negative. Thus, the power is negative, implying that the motor operates in braking mode. The mode of operation is known as **reverse braking** or as a **reverse generating**.

TOPIC 1 – SUMMARY

[INTRODUCTION TO ELECTRICAL DRIVE]

According to The IEEE Standard Dictionary of Electrical and Electronic Terms, an electric drives refers to a system that designed with combination of one or several electric motors with an electric control equipment that will perform as electric motors

Electrical drive is the combination of several electric motors which plays the role as electric control equipment that controls the motor's performance. The two main types of motor that can be used in electric drive are the DC motors and AC motors. TOPIC 1 emphasis more on the understanding of electrical drive itself, the advantages and block diagram that represent all main components of an electrical drive.

The characteristics of DC and AC motor speed torque were also being discussed in this chapter to show differences between DC and AC motor, hence hopefully will guide for a clear understanding.

Another focus that is being explained further is about the four quadrant operation in motor. The torque and speed co-ordination for forward and reverse motion of DC motor is also included for a better understanding of four quadrant operation in DC motor. By learning this topic and subtopic, students will completely understand how the speed torque and the braking system work together in an electrical motor drive system.

TIPS & TRICKS

(Souces : Ectricaltechnology,2021)

TOPIC 1 – TUTORIAL & ANSWER

[INTRODUCTION TO ELECTRICAL DRIVE]

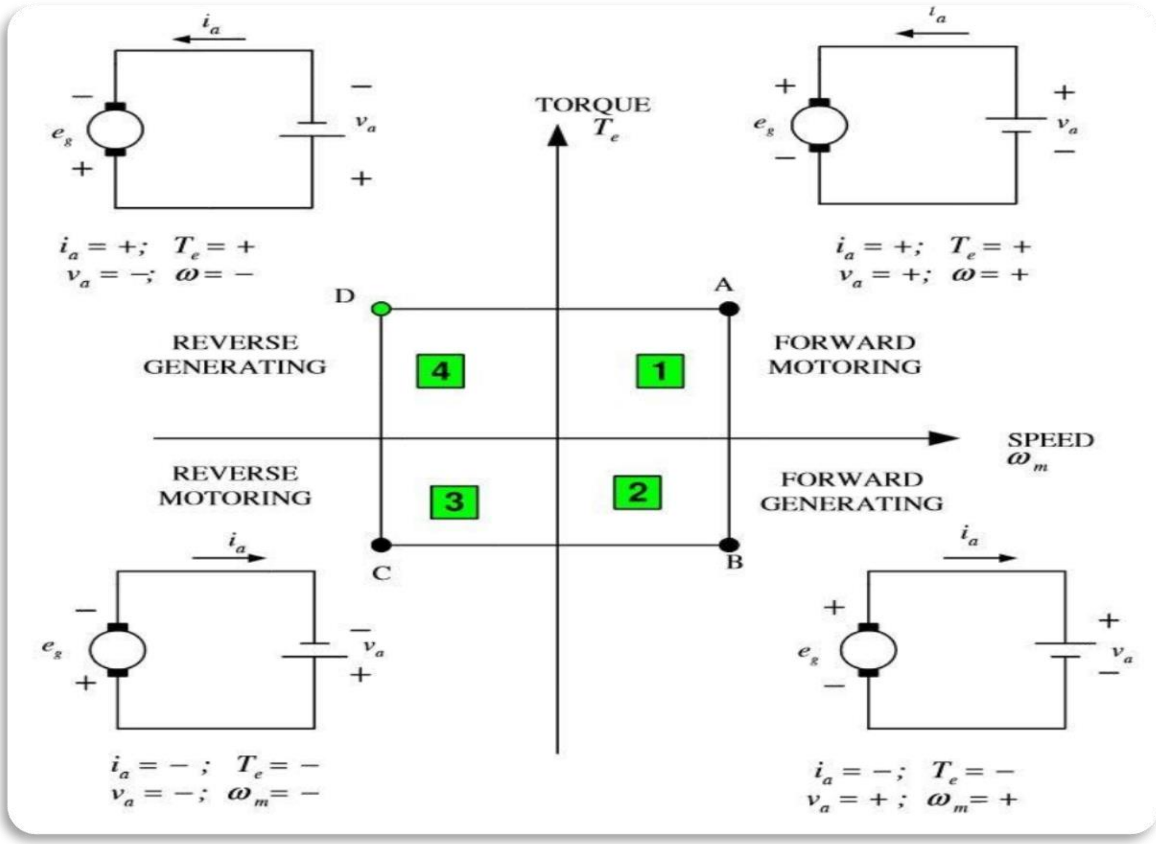
1. Define an electrical drive-in motor control.

Answer :

An electrical drive - an electromechanical device for converting electrical energy into mechanical energy. This process will impart motion to different machines and mechanisms for various kinds of process control. An electrical driver provides electrical control or electronic control of the process. It also can control the direction, speed, torque and other operating function of an electric motor in addition to providing motor protection and monitoring function.

2. Skecth the complete diagram of torque against speed for four quadrant control in DC motor operation.

Answer : →



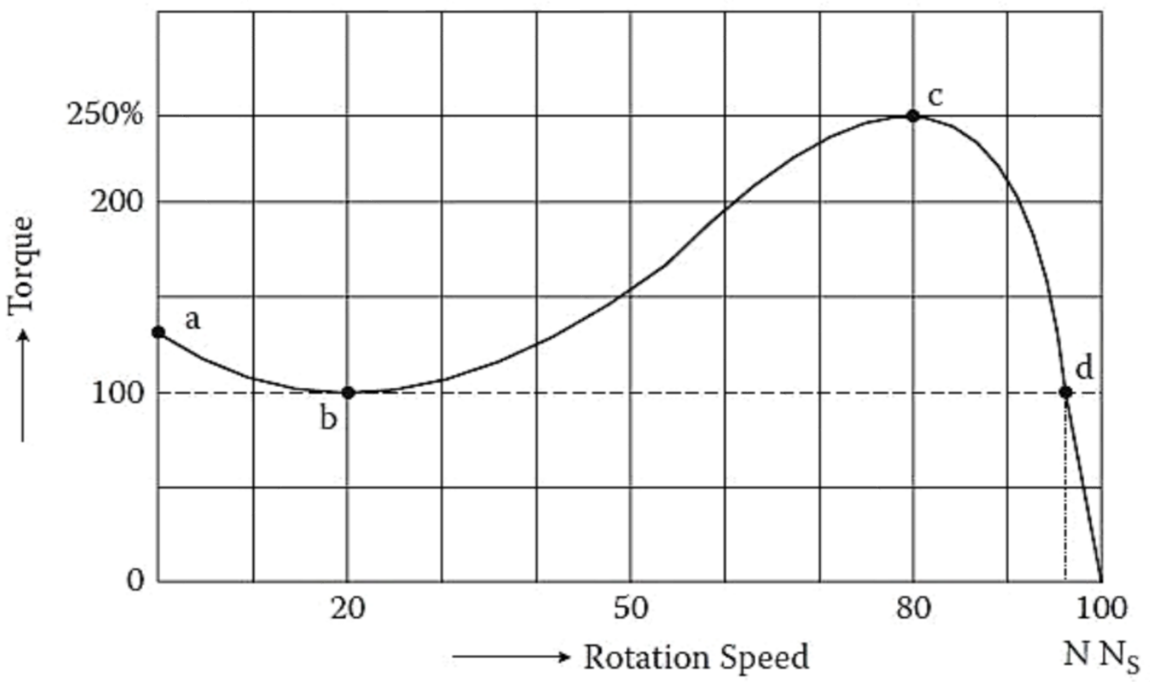
TOPIC 1 – TUTORIAL & ANSWER

[INTRODUCTION TO ELECTRICAL DRIVE]

3. Name each point (a,b,c and d) of the speed – torque characteristics curve for AC motor.

Answer : →

- Starting Torque / Lock rotor Torque
- Pull up Torque
- Breakdown Torque
- Full Load Torque



Speed–torque characteristic of an induction motor

TOPIC 1 – HOMEWORK

[INTRODUCTION TO ELECTRICAL DRIVE]

1. State SIX (6) advantages of using electrical driver.

2. Discuss the speed – torque curve of the induction motor based on the induction motor curve.

3. State the advantages of an electrical driver.

I. Flexible control characteristic and can be manipulated as per requirements.

II. Available in a wide range of speed, torque, and power.

III. The operation is pollution free.

IV. Electric braking can be employed in easily.

A. I, II, III B. I, III, IV C. II, III, IV D. I, II, III, IV

4. Figure 1A shows the block diagram of an electrical drive system. Recognize the element of B.

A. Electronic converter

B. Power Source

C. Controller

D. Motor

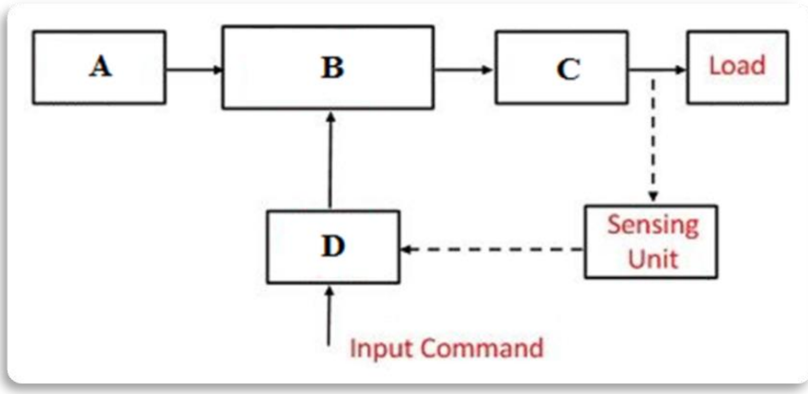


Figure 1A

TOPIC 2

BRAKING OF DC MOTOR

Upon completion of this topic, students should be able to:

- Understand the methods of slowing down a DC motor
- Apply the dynamic braking of DC shunt motor
- Apply the regenerative braking of DC shunt motor

DID YOU KNOW ?

Stopping is a special case for deceleration where the speed of motor is brought to zero
In application where
we need frequent, quick, smooth or emergency stop we need
Electrical Braking
as it affects less to the mechanical parts

(Source: Electricalbaba)

Hybrid and fully electric cars use regenerative braking systems to charge the batteries.
©ISTOCKPHOTO/TIM MCCAIG

Regenerative braking systems are particularly effective in stop-and-go driving conditions.
©ISTOCKPHOTO/DAVE HERRIMAN

TOPIC 2 – BRAKING OF DC MOTOR

2.1 Braking Of Electric Motor

In general, the term 'braking' is used to explain a group of operating conditions for electric drive systems. It includes rapid stopping of the electric motor, holding the motor shaft to a specific position, maintaining the speed to a desired value, or preventing the motor from over speeding.

All these aspects of braking are done electrically without applying any mechanical brakes. During the braking process, the energy can change its flow between the electric source and mechanical load. Electric braking is a highly efficient and low-maintenance technique compared to mechanical braking. Generally, braking methods can be grouped into two types:

- Dynamic braking
- Regenerative braking

2.2 Dynamic Braking Of DC Motor

Dynamic braking also known as rheostatic braking. In dynamic or rheostatic braking, the DC motor is disconnected from the supply and a braking resistor R_b is instantly connected across the armature. The motor will now work as a generator and produces the braking torque.

During electric braking when the motor works as a generator, the kinetic energy stored within the rotating parts of the motor and a connected load is converted into electricity. It is dissipated as heat in the braking resistance, R_b and armature circuit resistance, R_a. Dynamic braking is an inefficient method of braking as all the generated energy is dissipated as heat in resistances.

TOPIC 2 – BRAKING OF DC MOTOR

2.2 Dynamic Braking Of DC motor

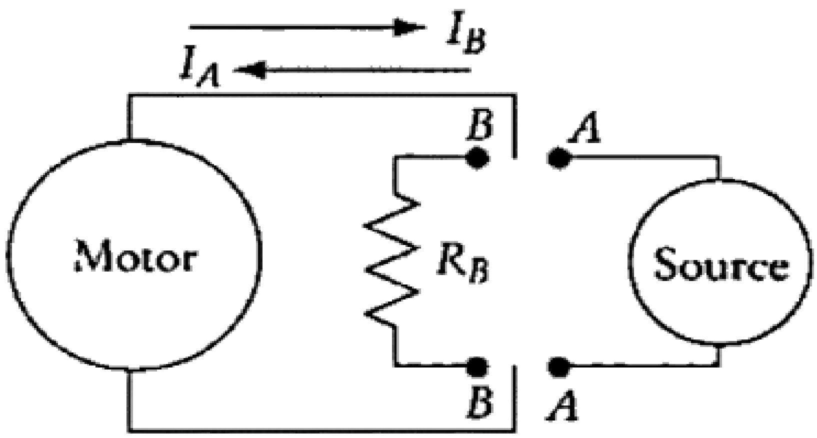


Figure 2.1 – Dynamic braking of DC motor
(Sources: El-Sharkawi, 2018)

When the **machine is connected to terminal A, it runs as a motor**. While the motor is rotating, it acquires kinetic energy stored in its rotating mass. The current I_A flows into the machine.

If the **terminals of the motor are switched to position B**, the **energy stored** within the rotating mass is **dissipated** in the braking resistance R_B. This is possible when the machine maintains its field. The braking current I_B flows out of the machine. The smaller the resistor is, the faster the energy is dissipated, and the faster the motor brakes.

When the **machine is working during a a dynamic braking mode, it acts as a generator**. The speed of the machine does not change its direction of rotation during braking, but the machine torque reverses its direction (I_B is opposite to I_A).

TOPIC 2 – BRAKING OF DC MOTOR

2.3 Regenerative braking of DC motor

Regenerative Braking is an example of braking during which the kinetic energy of the motor is returned to the power supply system. This type of braking is feasible when the driven load forces the motor to run at a speed above its no-load speed with a constant excitation. The motor back *emf* E_b is bigger than the supply voltage V, which reverses the direction of the motor armature current. Hence, the motor will operate as an electric generator.

However, the used of regenerative braking method here is not to stop a motor but rather to regulate the motor's speed above the no-load speed of the motor that drives the descending loads. An electric motor is in regenerative braking when the load torque reverses its direction and causes the machine to run at a speed higher than its no-load speed but without changing the direction of rotation.

An example of regenerative braking is given in Figure 2.2 below, where an electric motor is driving a trolley bus within the uphill and downhill directions. In the uphill direction, the gravity force can be resolved into two components:

- one perpendicular to the road surface F, and
- the other parallel to the road surface Fl

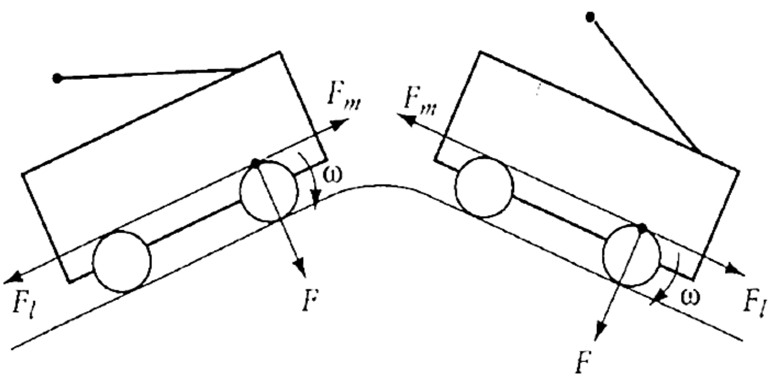


Figure 2.2 – Example of regenerative braking of DC motor
(Sources: El-Sharkawi, 2018)

2.3 Regenerative Braking Of DC motor

The parallel force F_l pulls the motor towards the bottom of the hill. If the rotational losses is ignored, the motor must produce a force F_m opposite to F_l to move the bus in the uphill direction. Note that the motor torque and speed are in the same direction, and the load torque T_l is opposite to the motor torque T_m. The power flow is from the motor to the mechanical load.

Now assume that the same bus is traveling downhill. Since the gravity does not change its direction, the load torque pushes the motor down towards the hill. The **direction of the motor torque is always opposite** to the direction of **the load torque**, so the motor produces a torque in the reverse direction.

Note that the rotation of the motor is still in the same direction on both sides of the hill. **This is known as regenerative braking.**

The energy exchange under regenerative braking is from the mechanical load to the electrical source. Hence, the load is driving the machine, and the machine is generating electric power that is returned back to the supply.

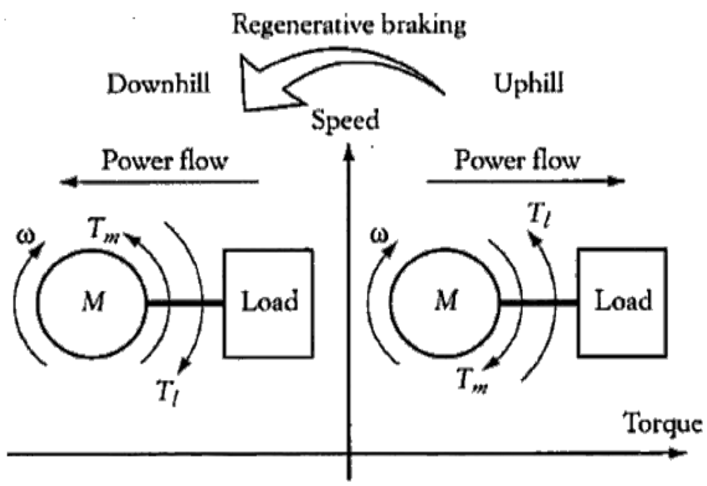


Figure 2.3 – Regenerative braking in second quadrant
(Sources: El-Sharkawi, 2018)

TOPIC 2 – BRAKING OF DC MOTOR

2.4 Dynamic Braking Of DC Shunt Motor

Dynamic braking is employed to stop the motor by dissipating its stored kinetic energy into a resistive load. Once the kinetic energy is completely dissipated, the motor stops rotating if no external torque is exerted.

Assume that the machine is running at a speed ω when dynamic braking is applied. The terminals of the armature circuit are disconnected from the power supply and connected across a braking resistance R_b.

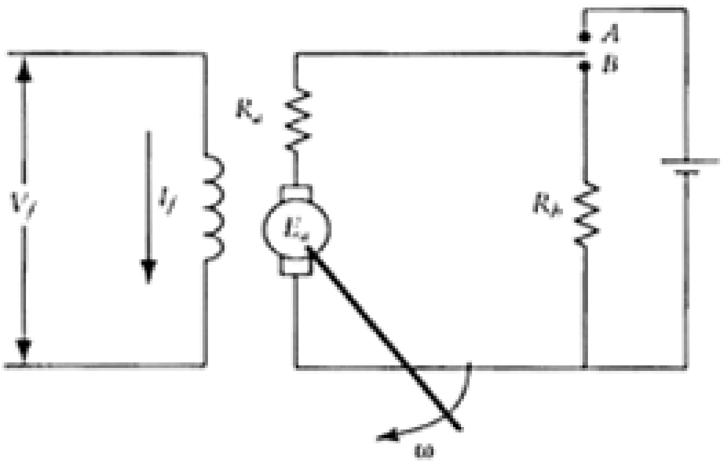


Figure 2.4 – Circuit diagram for dynamic braking Of DC Shunt Motor
(Sources: *El-Sharkawi, 2018*)

The field circuit is additionally disconnected from the armature circuit but remains excited by the source. Under this condition, the back *emf* Ea, is the voltage source of the armature circuit.

The braking current in this case is :

$$I_b = -\frac{E_a}{R_a+R_b} = -\frac{k\phi\,\omega}{R_a+R_b} \qquad \rightarrow \textit{equation 2.1}$$

TOPIC 2 – BRAKING OF DC MOTOR

2.4 Dynamic Braking Of DC Shunt Motor

The negative sign in Equation 2.1 indicates that the braking current is in the reverse direction of the armature current.

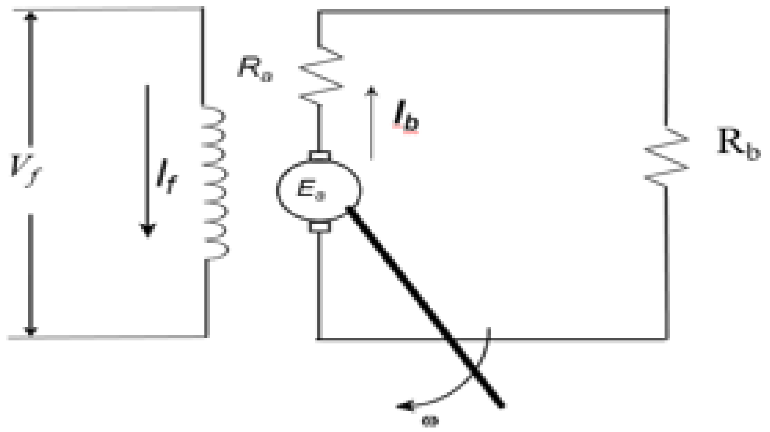


Figure 2.5 – Equivalent circuit diagram for dynamic braking current of DC shunt motor.
(Sources: El-Sharkawi, 2018)

The power dissipated during the dynamic braking consists of two major components:

- The first is mechanical losses (or rotational losses), which are due to friction and wind age losses.
- The second component is electrical losses P_b within the armature and braking resistances.

The electrical loss is mainly responsible for dissipating the motor's kinetic energy. The braking time is shorter if the electric losses are larger.

These losses can be calculated as:

$$P_b = \frac{E_a^2}{R_a + R_b} = \frac{(K\phi\omega)^2}{R_a + R_b} \qquad \rightarrow \textit{equation 2.2}$$

Equation (2.2) indicates that more electric power is dissipated if the braking resistance R_b is small and the field ϕ is strong.

2.5 Speed-current Characteristics Under Dynamic Braking

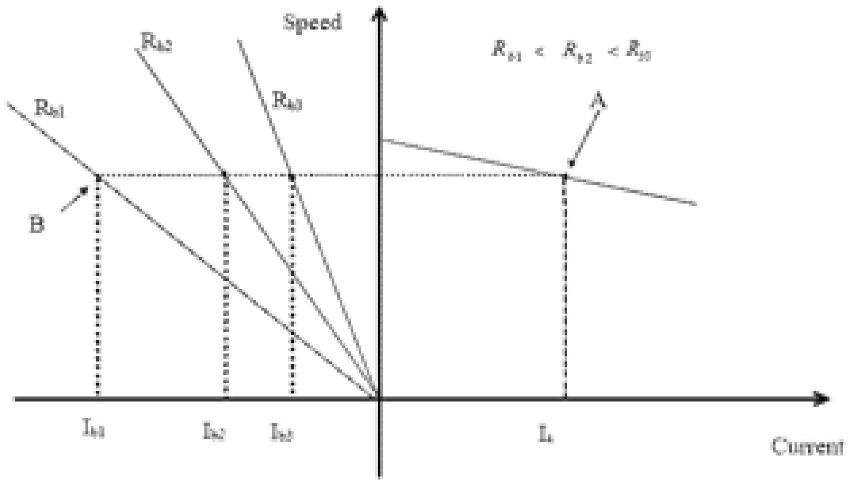


Figure 2.6 – Speed-current characteristics under dynamic braking
(Sources: El-Sharkawi, 2018)

The first quadrant of the graph is for normal motor operation, where the motor is operating at point A (refer to Figure 2. 6). Since the speed direction is unchanged and the current direction is reversed, the motor during dynamic braking is in the second quadrant.

During dynamic braking, the speed-current characteristics are all straight lines with negative slopes that intercept at the point of origin. The Figure 2.6 shows the speed-current characteristics for three different values of braking resistance, where $R_{b1} < R_{b2} < R_{b3}$.

The smaller the braking resistance is, the larger the braking current, and then higher is the rate by which the kinetic energy is dissipating. This situation results in **faster braking**.

2.6 Dynamic Braking Of Gravitational Torque Load

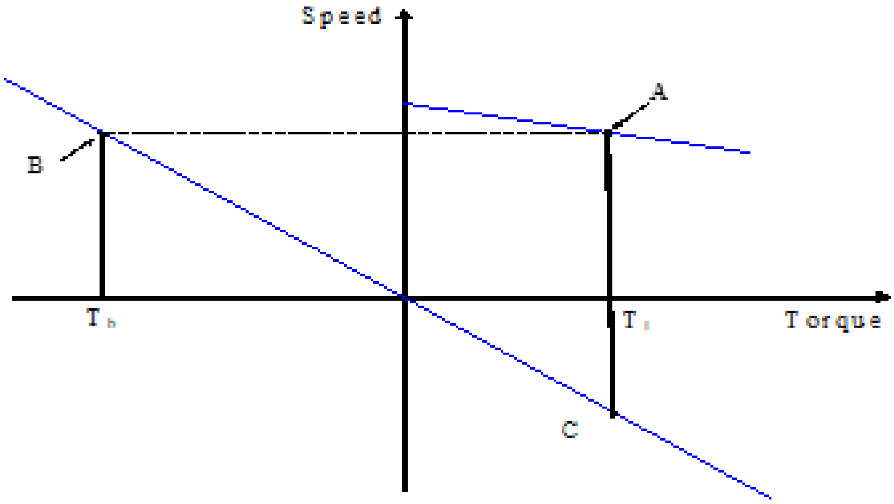


Figure 2.7 – Dynamic braking of gravitational torque load
(Sources: El-Sharkawi, 2018)

When the switch is in position A, the motor operates at point A. The armature current I_a flows from the source to the motor (refer to Figure 2. 6). By connecting the switch to terminal B, the voltage source is disconnected and the resistance R_b is inserted across the motor terminals. The operating point is shown and labeled B for $R_b = R_{b1}$.

If the switching from A to B is done quickly enough, one can assume that the motor speed during the switching interval is unchanged. After switching to B, the operating point of the motor moves horizontally to point B. At this point the armature current is I_{b1} which flows in the opposite direction to I_a. This current is flowing from the machine to the braking resistance.

When dynamic braking is applied, the motor operating point moves to B. The final destination of the operating point is when the motor torque meets the load torque, which occurs only in the fourth quadrant at point C. Hence, the operating point of the motor moves from B to the point of origin, then continues to point C.

2.6 Dynamic Braking Of Gravitational Torque Load

The **motor stops momentarily when the operating point reaches the origin**. If the load is disconnected or a mechanical brake is applied at the origin, the motor stops. Otherwise, the motor speed reverses its direction until the machine reaches point C.

The operation at point C is a typical generator operation in which the motor is driven mechanically by a unidirectional torque. The motor under this condition delivers electric power to the electrical load resistance R_b. For gravitational load, the load torque is assumed constant. Such a torque is constant regardless of the motor speed.

Table 2.1 below summarizes the general operation of the dynamic braking for a gravitational load.

Table 2.1 – Summary of the dynamic braking for a gravitational load
(Sources: El-Sharkawi , 2018)

Operating point	Motor Torque	Terminal Voltage	Armature current	Speed	Field	E_a	Comments
A	$\longrightarrow$ T_l	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$ ω_A	$\longrightarrow$	$\longrightarrow$ $E_{aA} < V_t$	Motor
B	$\longleftarrow$ T_b	0	$\longleftarrow$	$\longrightarrow$ $\omega_B = \omega_A$	$\longrightarrow$	$\longrightarrow$ $E_{aB} = E_{aA}$	Generator
Origin	0	0	0	0	$\longrightarrow$	0	No Load
C	$\longrightarrow$ T_l	0	$\longrightarrow$	$\longleftarrow$ ω_C	$\longrightarrow$	$\longleftarrow$ E_{aC}	Generator

TOPIC 2 – BRAKING OF DC MOTOR

2.7 Regenerative Braking Of DC Shunt Motor

Regenerative braking occurs when the load torque reverses its direction and causes the machine to run at a speed higher than its no-load speed but without changing the direction of rotation.

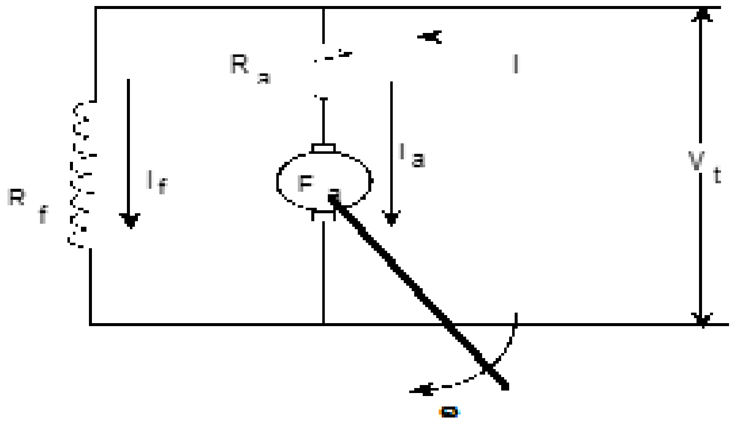


Figure 2.8 – Circuit diagram for regenerative braking of DC shunt motor
(Sources: El-Sharkawi, 2018)

2.8 Speed-torque Characteristics Under Regenerative Braking

Under given operating conditions, when the speed of the DC machine exceeds its no-load speed, the machine is in the regenerative braking mode.

Operating at point 1

The load torque in Figure 2.9 is assumed to be bidirectional, which is the case for the electric bus we are discussing. In the first quadrant, the machine operates as a motor. Let us assume that **operating point 1** represents this case.

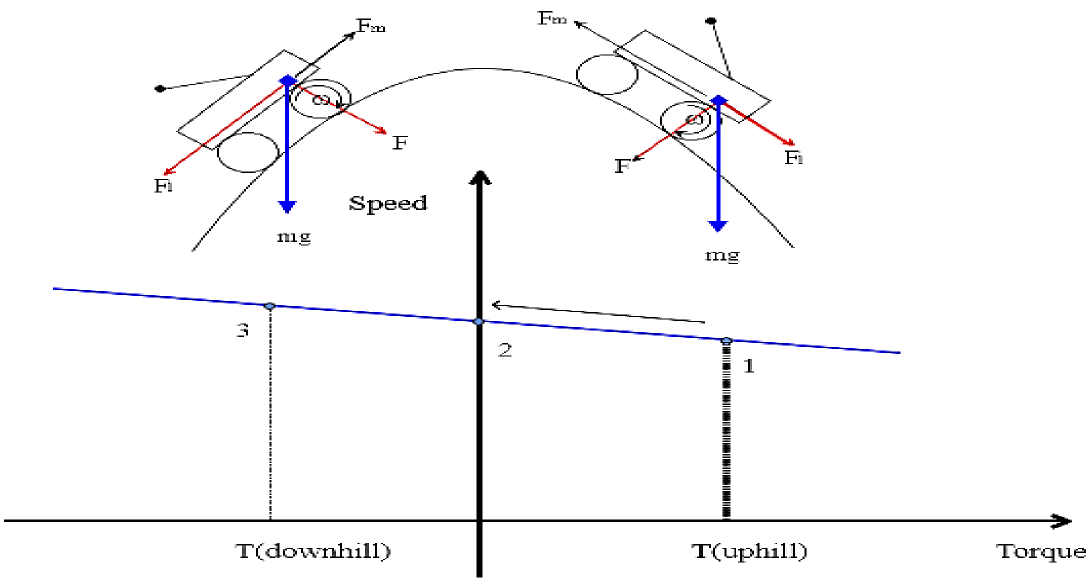


Figure 2.9 – Speed-torque characteristics under regenerative braking
(Sources: El-Sharkawi, 2018)

2.8 Speed-torque characteristics under regenerative braking

In the uphill direction, the DC machine acts as a motor represented by equations (2.3) to equations (2.5).

$$V_t = Ea + RaIa = K\phi\omega + \frac{R_a}{K\phi}T_l \qquad \rightarrow equation\ 2.3$$

$$\omega = \frac{V_t}{K\phi} - \frac{R_a}{(K\phi)^2}T_l \qquad \rightarrow equation\ 2.4$$

$$I_a = \frac{V_t - Ea}{R_a} = \frac{T_l}{K\phi} \qquad \rightarrow equation\ 2.5$$

The load torque in this case is opposite to the direction of the bus motion, and the drive system is in the first quadrant as shown in Figure 2.9. The equivalent circuit of the motor **operation at point 1** is shown at figure 2.10 below :

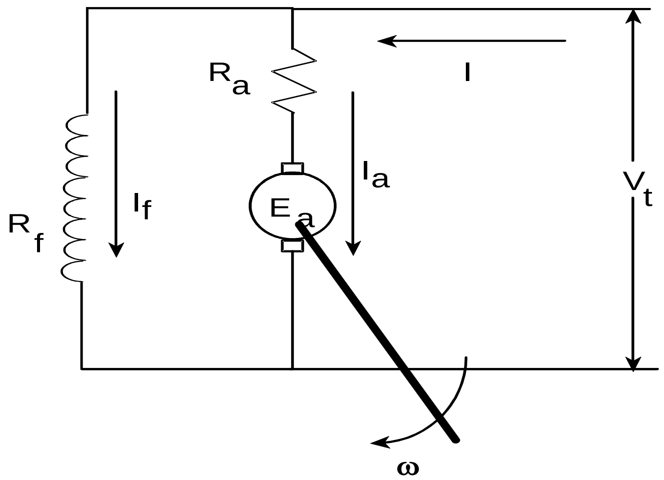


Figure 2.10 – Motor Operation at point 1
(Sources: El-Sharkawi, 2018)

Operating at point 2

When the bus reaches the peak of the hill, the load torque seen by the motor is zero, assuming that the frictional torque is ignored. This is because the gravitational torque at the top of the hill is perpendicular to the road surface and is not pulling the motor in either direction of motion.

2.8 Speed-torque characteristics under regenerative braking

Operating at point 2

Point 2 is used here to represent the operation of the motor at the top of the hill. Because the load torque at the top of the hill is zero, the armature current must also be zero. Since the current is zero, the voltage drop across the armature resistance is also zero. Equations (2.6) to (2.8) are represented by operating point 2. This operating point is the no-load operating point of a dc machine.

$$\omega_2 = \frac{V_t}{K\phi}$$ *→ equation 2.6*

$$I_{a_2} = \frac{V_t - Ea_2}{R_a} = \frac{T_{l_2}}{K\phi} = 0$$ *→ equation 2.7*

$$V_t = Ea_2$$ *→ Equation 2.8*

Operating at point 3

At this operating point, T_{l3} is negative. Since I_{a3} is negative, as seen in E_{a3} must be larger than V_t. Thus, the motor is operating as a generator. If the armature current is larger than the field current, the current $I = I_{a3} - I_f$ flows into the source. E_{a3} does not change its direction since ω and $K\phi$ are in the same direction as at point 1. The motor is now generating electric power and delivering it to the source. The **machine acts as a motor when $E_a < V_t$** and the **machine is a generator when $E_a > V_t$**.

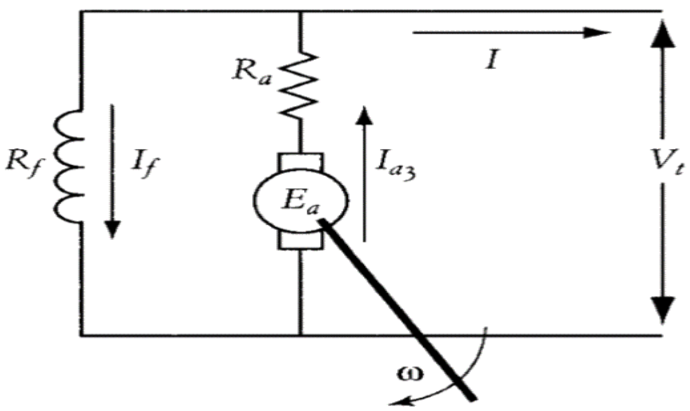


Figure 2.11 – Motor operation at point 3
(Sources: El-Sharkawi, 2018)

2.8 Speed-torque Characteristics Under Regenerative Braking

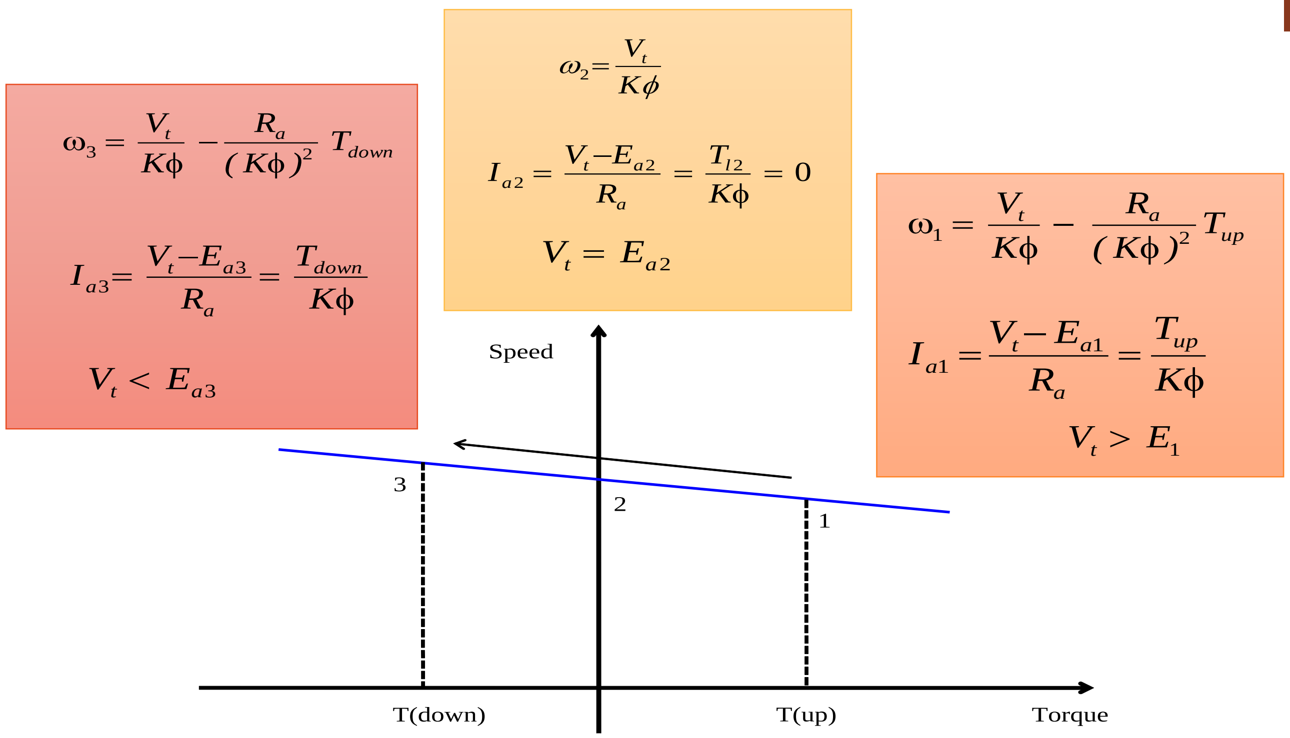


Figure 2.12 – Summary of equations for regenerative braking
(Sources: El-Sharkawi, 2018)

2.9 Back *emf* During Regenerative Braking

- The machine acts as a motor when $E_a < V_t$
- The machine is a generator when $E_a > V_t$

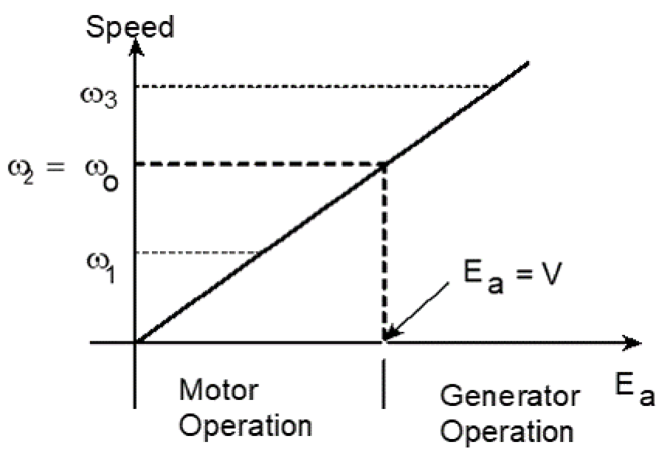


Figure 2.13 – Back *emf* during regenerative braking
(Sources: El-Sharkawi, 2018)

2.10 Summary of regenerative braking

Table 2.2 below summarizes the general operation of regenerative braking.

Table 2.2 – Summary of regenerative braking
(Sources: El-Sharkawi, 2018)

Operating point	Load Torque	Terminal Voltage	Armature current (I_a)	Speed	Field current (I_f)	E_a	Comments
1	→	→	→	→ $\omega_1 < \omega_0$	→	→ $E_{a1} < V_t$	Motor
2	0	→	0	→ $\omega_2 = \omega_0$	→	→ $E_{a2} = V_t$	No Load
3	←	→	←	→ $\omega_3 > \omega_0$	→	→ $E_{a3} > V_t$	Generator

TOPIC 2 – SUMMARY

[BREAKING OF DC MOTOR]

TOPIC 2 strengthen the student's knowledge more into specific details of DC motor braking motor. General introduction about methods of slowing down DC motor were being explained to help better understanding of students.

Students were introduced with the chart or diagram and equation formulae that represent the characteristics of DC shunt motor for both, dynamic braking and regenerative braking. A few examples on problem solving is given in this chapter.

TIPS & TRICKS

Tips & Tricks

$$I_b = -\frac{E_a}{R_a + R_b} = -\frac{k\phi\omega}{R_a + R_b}$$

→ How to calculate dynamic braking current of DC shunt motor

$$P_b = \frac{E_a^2}{R_a + R_b} = \frac{(K\phi\omega)^2}{R_a + R_b}$$

→ How to calculate dynamic braking losses of DC shunt motor

$$\omega_3 = \frac{V_t}{K\phi} - \frac{R_a}{(K\phi)^2} T_{down}$$

$$I_{a3} = \frac{V_t - E_{a3}}{R_a} = \frac{T_{down}}{K\phi}$$

$$V_t < E_{a3}$$

$$\omega_2 = \frac{V_t}{K\phi}$$

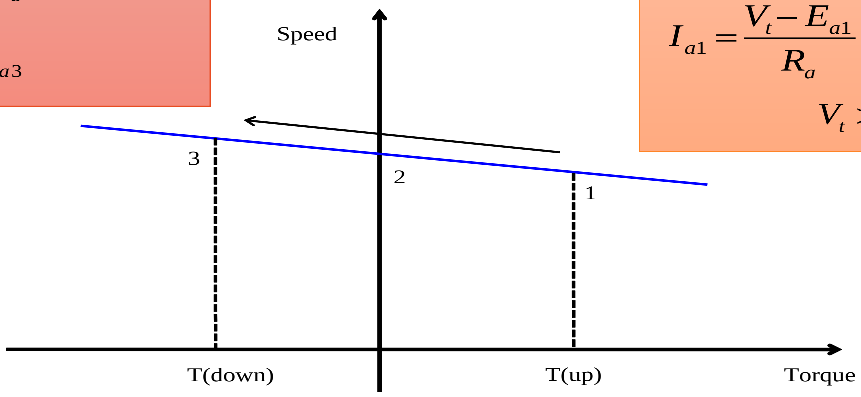
$$I_{a2} = \frac{V_t - E_{a2}}{R_a} = \frac{T_{l2}}{K\phi} = 0$$

$$V_t = E_{a2}$$

$$\omega_1 = \frac{V_t}{K\phi} - \frac{R_a}{(K\phi)^2} T_{up}$$

$$I_{a1} = \frac{V_t - E_{a1}}{R_a} = \frac{T_{up}}{K\phi}$$

$$V_t > E_1$$



→ How to calculate speed, current and emf in regenerative braking of DC shunt motor

TOPIC 2 – TUTORIAL & ANSWER

[BREAKING OF DC MOTOR]

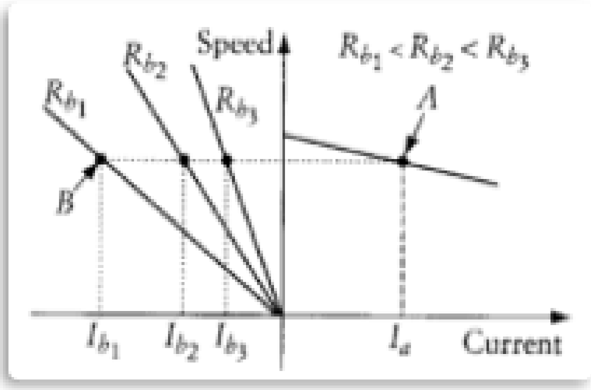
1. Describe the dynamic braking of a DC motor.

Answer : →

Dynamic braking is used to stop the motor by dissipating its stored kinetic energy into resistive load. The terminals of the armature circuit are disconnected from the power source and connected across the braking resistor. The motor continues to rotate for a period of time until the stored energy is totally dissipated in the form of rotational losses. The kinetic energy of the motor is transformed into electrical energy and dissipated into a resistive load.

2. Discuss the effects of motor current for different resistance under dynamic braking method of a DC motor with the aid of speed-current curve.

Answer : →



When the motor operates at point A, the armature current I_a flows from the source to the motor. The voltage source is disconnected and the resistance R_b is inserted across the motor terminals. The operating point is labelled B for $R_b = R_{b1}$. At this point the armature current is I_{b1}, which flows in the opposite direction to I_a. This current is flowing from the motor to braking resistance. If R_b is changed to the larger braking resistance R_{b2}, the armature current I_{b2} flows smaller than I_{b1}

3. A 440 V, DC shunt motor has a rated armature current of 76 A at a speed of 1000 rpm. The armature resistance of the motor is 0.377 Ω and the field resistance is 110 Ω. Assume that the load torque is gravitational. The current of the motor is 40 A at the steady state condition. A dynamic braking technique employing a braking resistance of 2 Ω is used to slow down the motor. Calculate the new steady state speed.

Answer :

The new steady state speed:

$$E_a = V_t - I_a R_a = 440 - 76(0.377) = 411.348 \text{ V}$$

$$\omega = \frac{2\pi n}{60} = \frac{2\pi(1000)}{60} = 104.720 \text{ rad/sec}$$

$$K\Phi = \frac{E_a}{\omega} = \frac{411.348}{104.720} = 3.928 \text{ V sec}$$

$$I_b = -\frac{K\Phi\omega}{R_a + R_b}$$

$$40 = -\frac{3.928\omega}{0.377 + 2}$$

$$\omega = -24.206 \text{ rad/sec}$$

$$n = \frac{60\omega}{2\pi} = \frac{60(-24.206)}{2\pi} = -231 \text{ rpm}$$

4. A DC motor of 440V has a rated armature current of 76 A at a speed of 1000 rev/min. The armature resistance of the motor is 0.377 ohm, the field resistance is 110 ohm and the rotational losses is 1 kW. The load of the motor is bidirectional. Calculate the following:

a) no load speed of the motor

b) the motor speed when the armature current is 60 A during regenerative braking

c) the developed load torque during regenerative braking

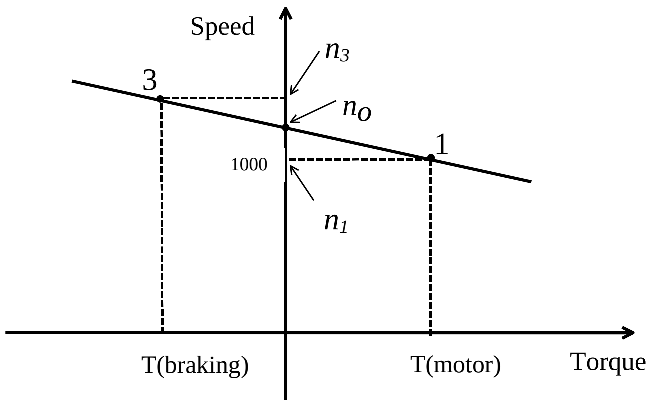
d) E_a during regenerative braking.

Answer →:

Point 1 represent the motor operation at rated current and 1000 rpm. During motor operation,

$$E_a = V_t - R_a\ I_a = 440 - 0.377 \times 76 = 411.35\ \text{V}$$

$$K\varphi = \frac{E_a}{\omega} = \frac{E_a}{2\pi \frac{n}{60}} = 3.93\ \text{V sec}$$



a)No- load speed of the motor ;

$$\omega = \frac{V_t}{K\varphi} - \frac{R_a}{(K\varphi)^2} T_{up}$$

$$\omega_o = \frac{V_t}{K\phi} = \frac{440}{3.93} = 111.96\ \text{rad/sec}$$

$$n_o = \frac{60 \times \omega_o}{2\pi} = 1069.1\, rpm$$

b) Point 3 represent during regenerative braking. The speed of the motor when the armature current is 60 A ;

$$\omega_3 = \frac{V_t}{K\phi} - \frac{R_a}{(K\phi)^2} T_{l3} = \frac{V_t - R_a I_{a3}}{K\phi} = \frac{440 + 0.377 \times 60}{3.93} = 117.72 \text{ rad/sec}$$

$$n_3 = \frac{60 \times \omega_3}{2\pi} = 1124.1 \; rpm$$

c) The developed load torque at point 3 during regenerative braking;

$$T_{l3} = K\phi \; I_{a3} = 3.93 \times (-60) = -235.8 \text{ Nm}$$

d) The back emf at point 3, E_{a3} during regenerative braking is;

$$\mathrm{E}_{a3} = \mathrm{K}\varphi\,\omega_3 = 3.93 \times 117.72 = 462.64 \;\; \mathrm{V}$$

1. With the aid of diagram, elaborate the concept of dynamic braking of a DC motor.

2. Based on Figure A1 below, complete the table of summary of dynamic braking DC shunt motor for gravitational load.

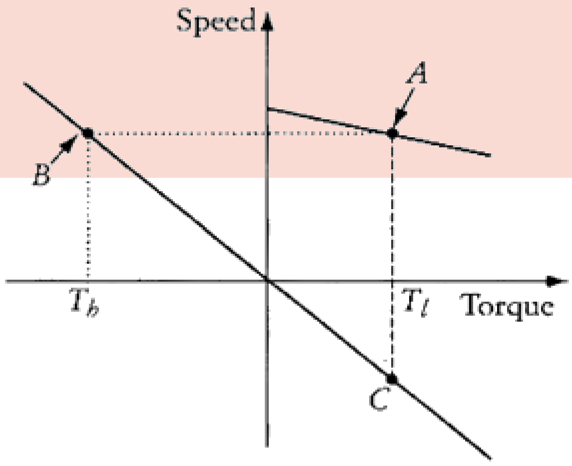


Figure A(1)

3. With the aid of a circuit diagram, demonstrate the concept of regenerative braking for a DC motor.

4. Figure A2 shows the circuit diagram dynamic braking, which is the correct statement relates to the power dissipation during dynamic braking.

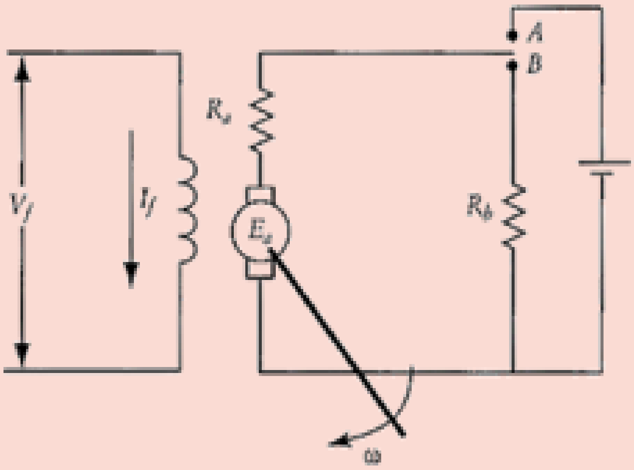


Figure A(2)

A. It is caused by one main component, which is mechanical losses.

B. It is caused by one main component, which is electrical losses.

C. It is caused by three main components, which are mechanical losses, electrical losses and others.

D. It is caused by two main components, which are mechanical losses and electrical losses.

5. Figure A3 shows the speed-torque characteristic of a DC shunt motor under regenerative braking. The motor received 440 V and the rated armature current of 76A at a speed of 1000 rpm. The armature resistance of the motor is 0.35Ω, and the field resistance is 110Ω, and the rotational losses are 1kW. The load of the motor is bidirectional. Calculate the no-load speed of the motor.

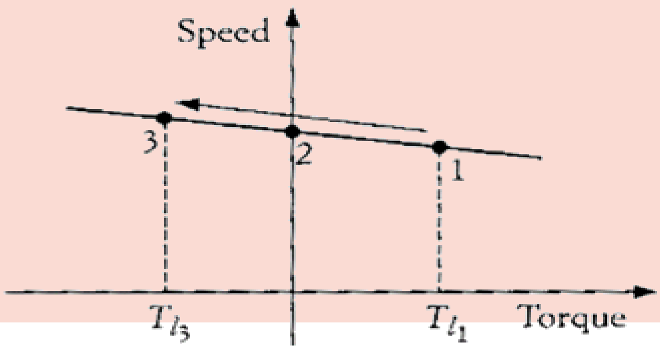


Figure A(3)

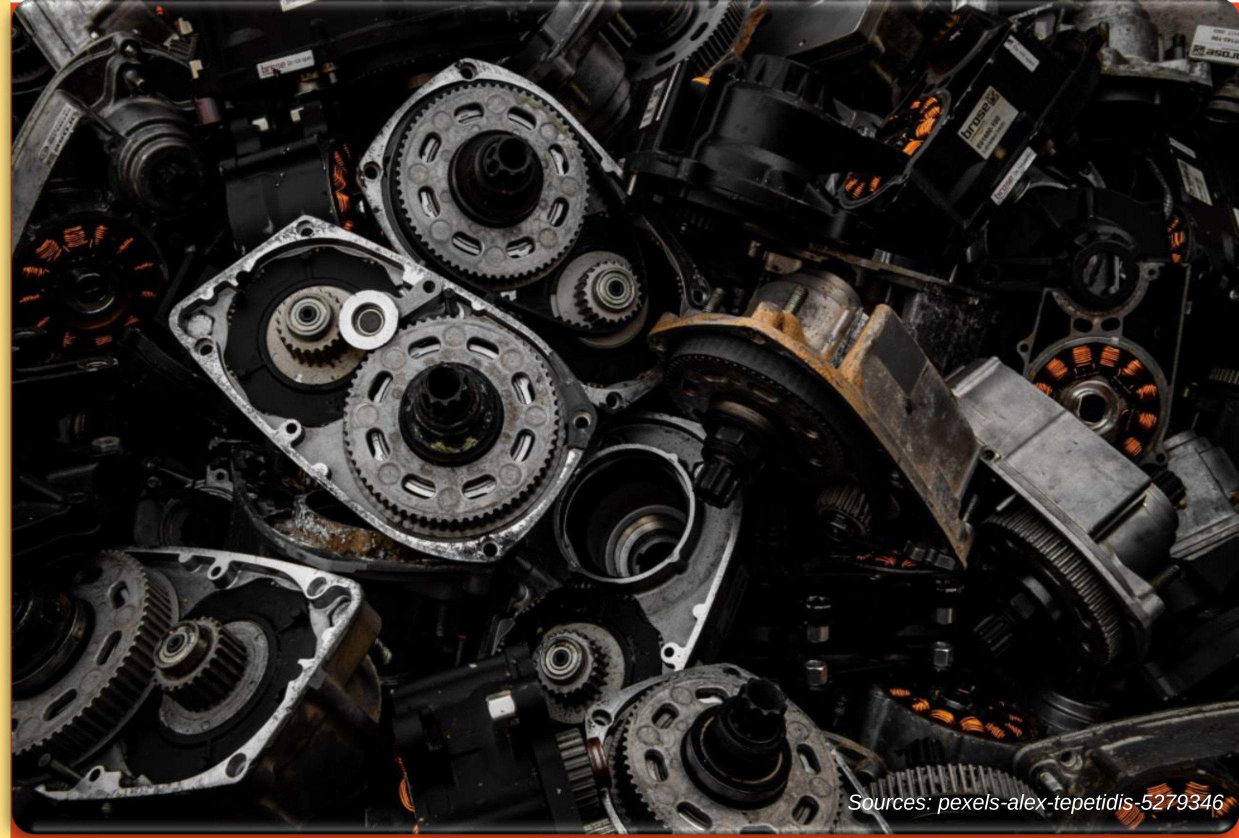
A. 1070.48 rpm

B. 1063.70 rpm

C. 1043.68 rpm

D. 1020.28 rpm

TOPIC 3



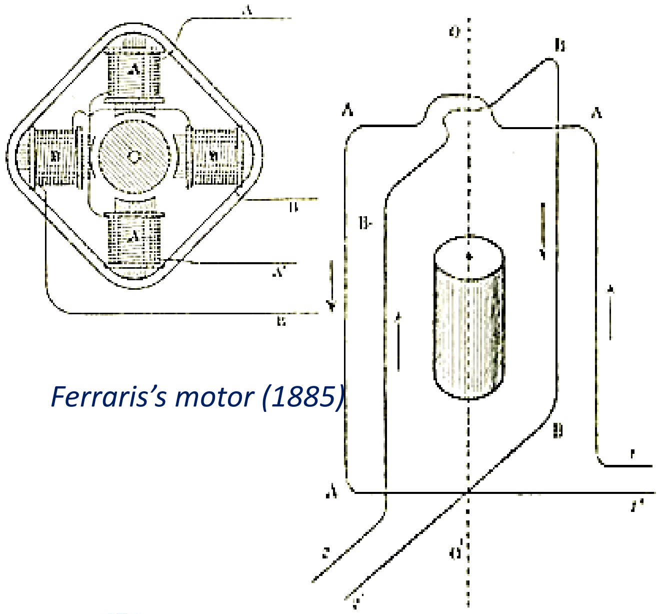
BRAKING OF AC MOTOR

Upon completion of this subtopic, students should be able to:

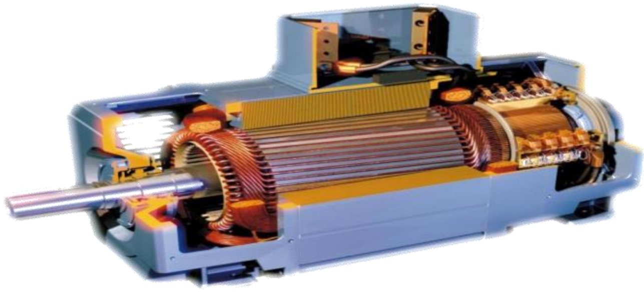
- Understand the methods of slowing down an AC induction motor
- Apply the dynamic braking of AC induction motor
- Apply the regenerative braking of AC induction motor
- Apply the DC injection braking of AC induction motor

DID YOU KNOW ?

Galileo Ferraris
(1847-1897)
Inventor of the Induction Motor



Ferraris's motor (1885)



- "Father of three-phase current" - Electrotechnical Congress, Frankfurt 1891
- Galileo Ferraris of Turin, Italy was the creator of the AC motor without a commutator (**Induction Motor**) and power transmission systems in 1888
- This efficient motor made AC power practical for many uses and launched AC power as the most popular form of electric power
- It was stated as "One of the greatest inventions of any age"
- His work helped others like Mikhail Dobrovsky and C.P. Steinmetz to further develop polyphase electric power
- However, Nikola Tesla claimed to the court as the inventor of induction motor in 1905 which Ferraris had lost!

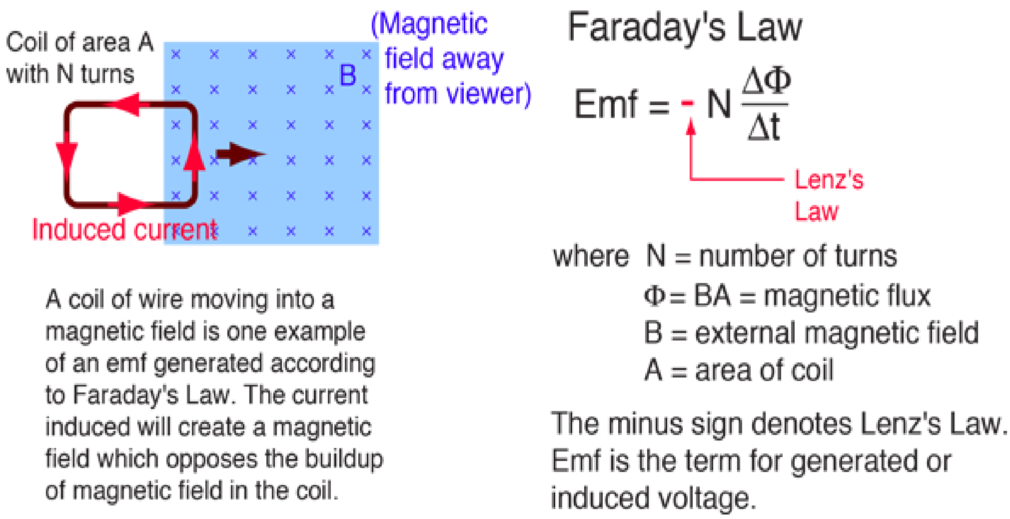
(Sources: Wikipedia, Galileo Ferraris)

TOPIC 3 – BRAKING OF AC MOTOR

3.1 Faraday's Law

Faraday's law is a fundamental relationship which comes from Maxwell's equations. It serves as a succinct summary of the ways a voltage (or *emf*) may be generated by a changing magnetic environment.

The induced *emf* in a coil is equal to the negative of the rate of change of magnetic flux times the number of turns in the coil. It involves the interaction of charge with magnetic field.



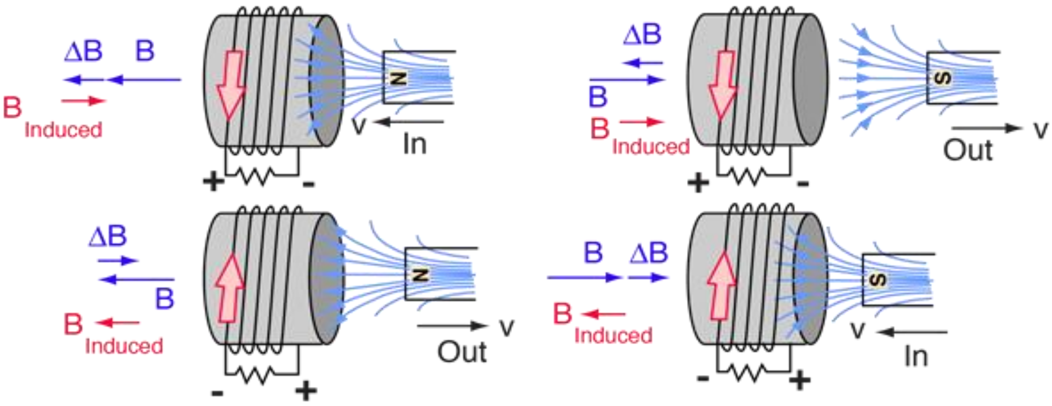
(Source : Hyperphysics)

TOPIC 3 – BRAKING OF AC MOTOR

3.2 Lenz's Law

When an *emf* is generated by a change in magnetic flux according to Faraday's Law, the polarity of the induced *emf* is such that it produces a current whose magnetic field opposes the change which produces it. The induced magnetic field inside any loop of wire always acts to hold the magnetic field in the loop constant. In the examples below, if the B field is increasing, the induced field acts in opposite direction to it. If it is decreasing, the induced field acts in the the direction of the applied field to try to maintain it constant.

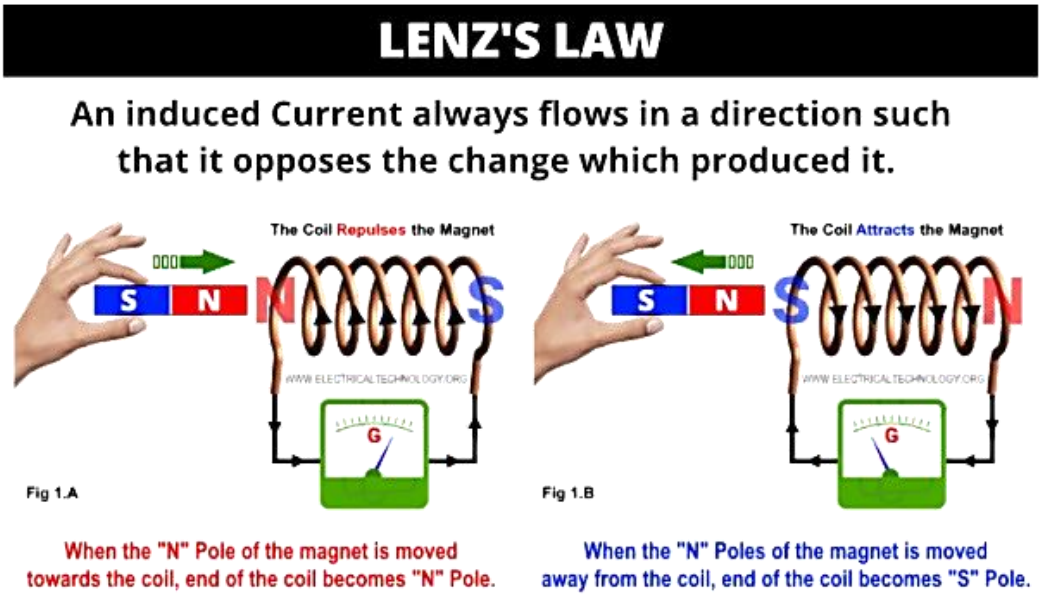
Emil Lenz, 1804 - 1865

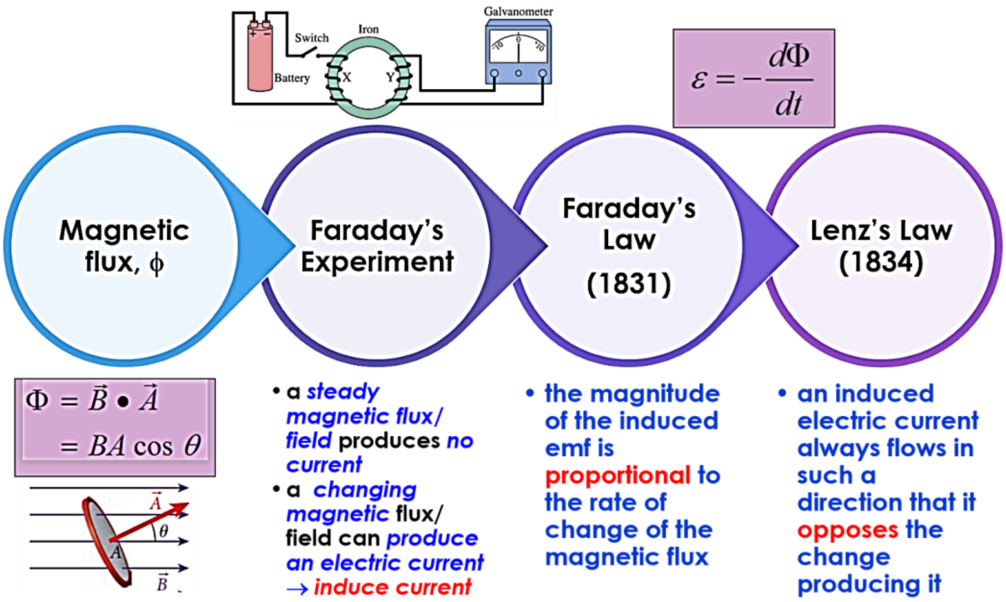


(Source : Hyperphysics)

TOPIC 3 – BRAKING OF AC MOTOR

3.3 Faraday's Law & Lenz's Law - Combined





(Source : Electromagnetic, 2018)

TOPIC 3 – BRAKING OF AC MOTOR

3.4 The AC Induction Motor

3.4.1 Introduction

The AC induction motor or asynchronous motor well suits application that requires constant speed operation. Basically, the construction of the induction motor is very simple and extremely rugged. Besides that, the induction motor is reliable, cheaper and easier to maintain compared to other alternatives.

There are basically two types of induction motor. The input supply determines the type of induction motor. Base on the input supply, the induction motors are classified **as single phase induction motor or three phase induction motor.**

Three phase induction motors are commonly utilized as industrial drives because they are self-starting and cost-effective. Single phase induction motors are not a self-starting motor and are often used for small loads such as household appliances such as fans.

3.4.2 Three Phase Induction Motor

The induction motor is made up of the stator circuit or stationary windings and the rotor circuit. The stator has three sets of very low resistance coils which are separated by 120° and are excited by three-phase supply in order to produce **rotating magnetic field**.

The rotor circuit is also made up of three-phase windings that are shorted internally (within the rotor structure) or externally (through slip rings and brushes). The rotor with internal short is called as **squirrel cage rotor** and the externally shorted is known as **slip ring rotor** *or* **wound rotor**.

TOPIC 3 – BRAKING OF AC MOTOR

3.4 The AC Induction Motor

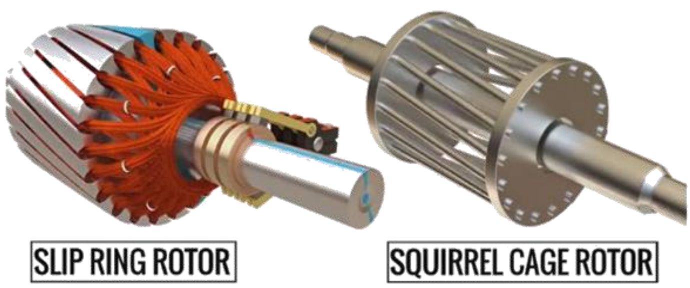


Figure 3.1 : Squirrel cage rotor and slip ring rotor
(Source: Moflon)

The three-phase induction motor are classified depending upon the type of rotor construction used. The two types of three phase induction motor are :

- squirrel cage induction motor
- slip ring induction motor or wound induction motor

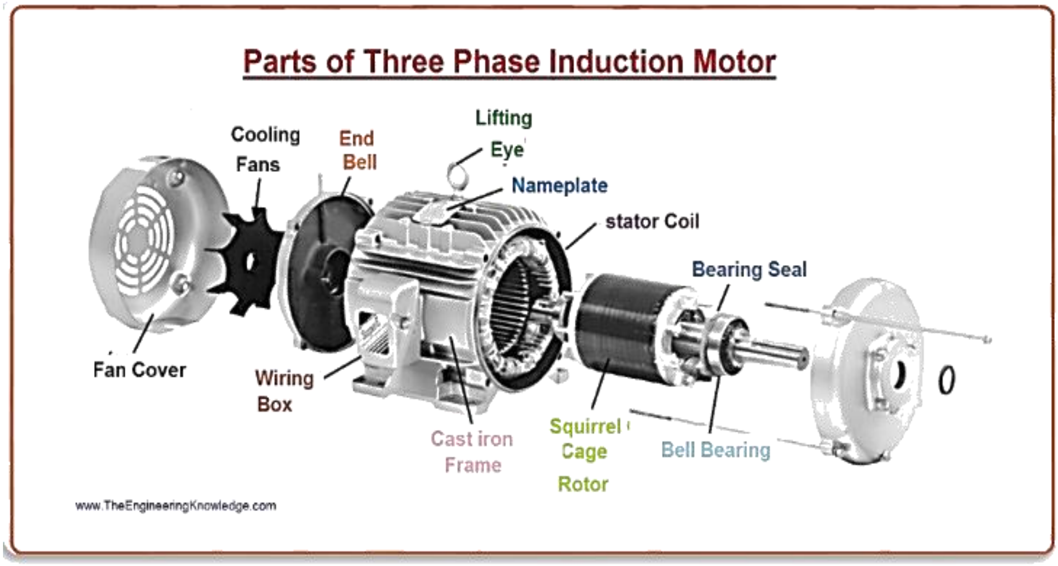


Figure 3.2 : Squirrel cage induction motor
(Source: Theengineeringknowledge)

3.5 Working Principle Of Three-Phase Induction Motor

Only the stator winding is powered by an AC source in an induction motor. Due to the AC supply, alternating flux is created around the stator winding. This alternating flux rotates at a synchronous rate. "Rotating Magnetic Field" is the term for the rotating flux (RMF).

According to *Faraday's Law*, the relative speed of the stator RMF and the rotor conductors induces an induced electromotive force (*emf*) in the rotor conductors. Because the rotor conductors are short-circuited, induced *emf* produces rotor current. Induction motors get their name from this circumstance.

Induced current in the rotor now produces alternating flux around it. The flux of the rotor is slower than (lags behind) the flux of the stator. According to *Lenz's law*, the direction of induced rotor current will tend to oppose the origin of its production.

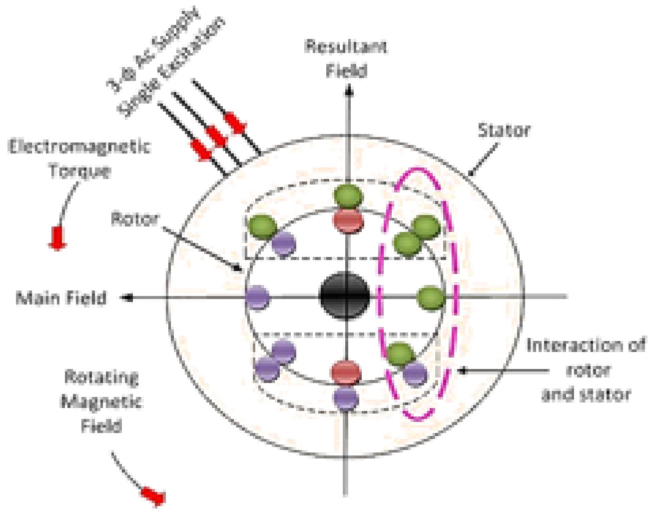


Figure 3.3 : The three-phase induction motor
(Source :Circuitglobe)

The rotor will strive to catch up with the stator RMF since the relative velocity between rotating stator flux and the rotor is the cause of rotor current production. To reduce the relative velocity, the rotor rotates in the same direction as the stator flux. On the other hand, the rotor never manages to catch up to the synchronous speed. This is the basic working principle of single phase or three phase induction motor.

3.6 Synchronous Speed

The synchronous speed is referred as the speed of the rotating magnetic field in the stator. The synchronous speed, n_s can be calculated as:

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

where, n_s = synchronous speed (rev/min, rpm)

f = frequency of the power supply (Hz)

p = number of poles

The speed of an induction motor is always lower than the synchronous speed.

3.7 Slip

The difference between the synchronous speed (n_s) and actual speed (n_r) of the rotor is called as slip, ***s.*** The slip, ***s*** can be calculated as:

$$S\,(\%) = \frac{n_s - n_r}{n_s} \times 100$$

where, s = slip of induction motor (%, percentage)

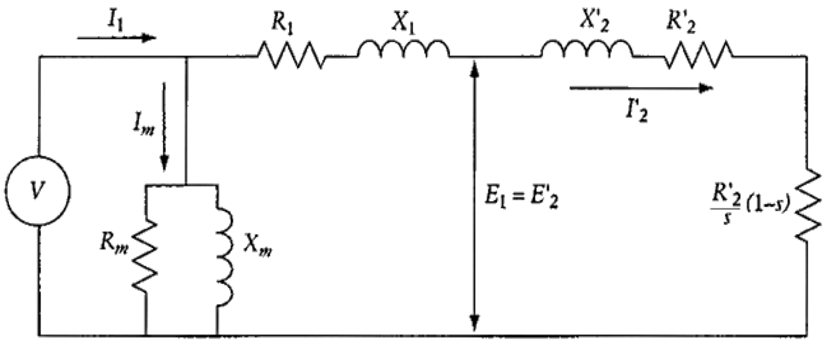
n_s = synchronous speed (stator) (rev/min, rpm)

n_r = rotor speed (rev/min, rpm)

The rotor of the three-phase induction motor is always running at the speed which is slightly below the synchronous speed of the induction motor. Rotor tries to catch up the synchronous speed of the stator field but in practice, rotor never succeeds in catching up (https://www.electrical4u.com).

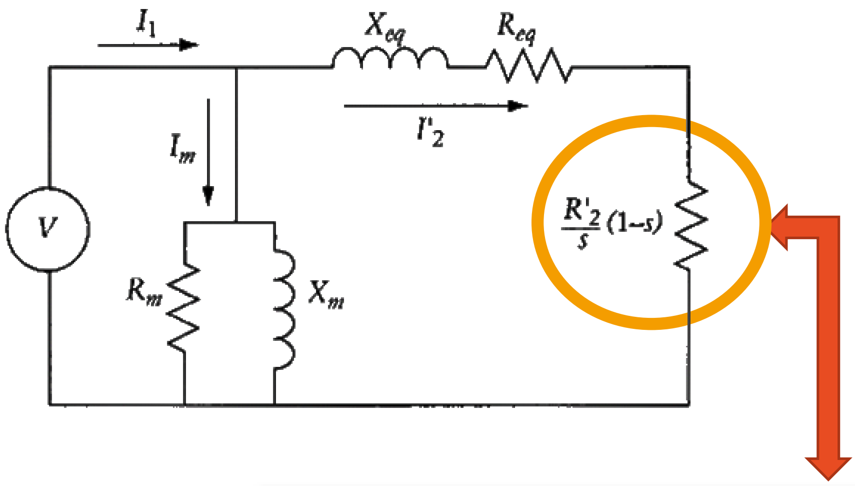
If rotor catches up the stator speed, there won't be any relative speed between the stator flux and the rotor. Thus, no induced rotor current and no torque to maintain the rotation. That is why the rotor rotates at speed which is always less the synchronous speed.

3.8 Equivalent Circuit of Induction Motor



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

$$X_{eq} = X_1 + X'_2$$



Represents the load of the motor, which includes the mechanical and rotational loads

(Sources: El-Sharkawi, 2018)

3.9 Power Flow of Induction Motor

- *Input power (P_{in})*
  - *Stator losses:*
    - *Copper losses (P_{cu1})*
    - *Core losses (P_{iron})*
  - *Airgap power (P_g)*
    - *Rotor Copper losses P_{cu2}*
    - *Developed power (P_d)*
      - *Rotational losses ($P_{rotational}$)*
      - *Output power (P_{out})*

Detailed power flow of the induction motor

- $P_{in} = 3VI_1 \cos\theta_1$
  - $P_{cu1} = 3I^2{}_1R_1$
  - $P_{iron} \cong 3\dfrac{V^2}{R_m}$
  - $P_g = 3(1'_2)^2\dfrac{R'_2}{s} = Td\omega_s$
    - $P_{cu2} = 3(I'_2)^2R'_2 = sPg$
    - $P_d = 3(1'_2)^2\dfrac{R'_2}{s}(1-s) = Pg\,(1-s) = Td\omega$
      - $P_{rotational}$
      - $P_{out} = T\omega$

(Sources: El-Sharkawi, 2018)

TOPIC 3 – BRAKING OF AC MOTOR

3.10 Dynamic braking of Induction Motor

Since the rotor is spinning solely because of its stored kinetic energy, the rotor losses reduce the overall kinetic energy of the motor, thus assisting the motor to stop. The stationary field for dynamic braking can be created using the circuit in figure 3.4 below. Instead of switching the transistor sequentially, here we close only three transistors for the duration of the dynamic braking (El-Sharkawi, 2018). Note that no two transistors on the same leg can be closed.

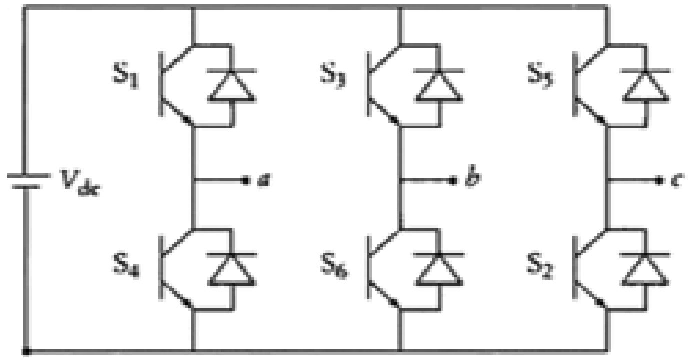


Figure 3.4 – Six-pulse drive circuit for creating stationary field
(Sources: El-Sharkawi, 2018)

Now, let us assume that S1, S5 and S6 are closed. As seen in Figure 3.1, the **terminals of phases a and c are positive potentials and that for phase b is negative.** The current in the stator winding is DC and will produce a stationary field in the air gap. Please take note that the resistance of the stator windings is usually very small and the inductive reactance has no impact on DC currents. Therefore, the current in the stator windings could be excessive unless the terminal voltage during braking is small enough (El-Sharkawi, 2018).

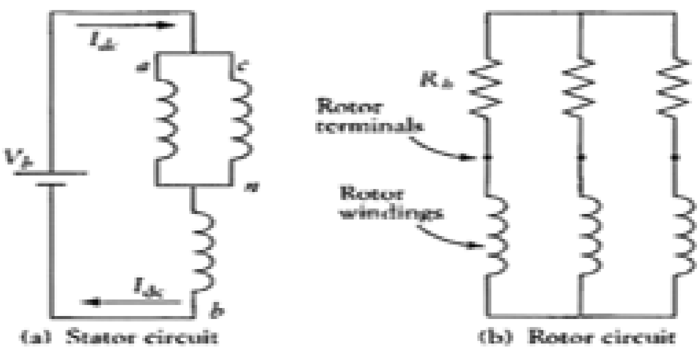


Figure 3.5 – Winding arrangements during dynamic braking
(Sources: El-Sharkawi, 2018)

3.10 Dynamic braking of Induction Motor

To reduce the voltage across the stator windings, PWM or FWM techniques are often used. To calculate the highest braking voltage, let us examine the stator circuit. Assume that the stator windings have only resistive elements (El-Sharkawi, 2018). The total DC current for this circuit are often calculated by :

$$I_{dc} = \frac{V_b}{1.5Rb} \leq Ib$$

Where

V_b = reduced voltage applied to the stator windings during dynamic Braking

R_b = resistance of single-phase windings

I_b = upper limit of the stator current during braking

Depending on the size of the motor and the braking time, I_b could be selected as high as three times the rated current. Remember that the shorter the braking time is, the larger the braking current. A larger braking current results in a stronger stationary field in the air gap, which induces larger current and higher losses in the rotor circuit.

3.11 Regenerative braking of Induction Motor

Regenerative braking occurs when the motor speed exceeds the synchronous speed. This may happen when the load torque drives the electric motor beyond its synchronous speed. In this case, the load is that the source of energy and therefore the induction machine is converting the mechanical power into electrical power, which is delivered back to the electrical system.

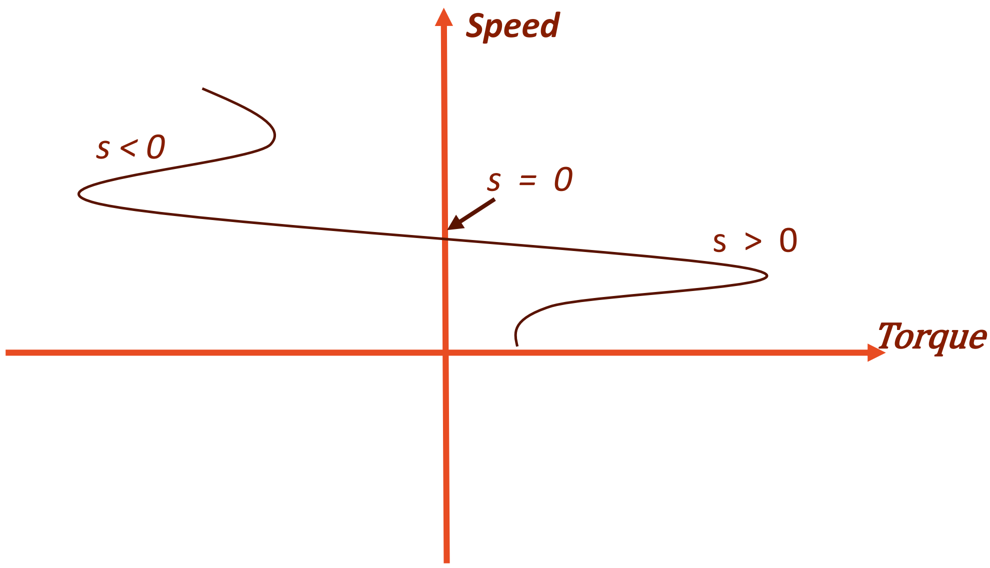


Figure 3.6 – Regenerative braking of induction motor
(Sources: El-Sharkawi, 2018)

Since the torque of the machine is negative during regenerative braking, but the direction of rotation of the machine is the same as that in the first quadrant, the flow of power is reversed.

The mechanical power is the source of energy and is converted to electrical power by the machine. This electrical power is delivered to the electrical system, and the machine is acting as generator.

3.12 DC injection braking

DC injection is a method of slowing down an induction motor. A DC voltage is injected into the winding of the AC motor after the AC voltage is disconnected at switch K1, providing braking force to the motor (https://wwwscribd.com/document/477012064).

A DC voltage is applied to the motor windings, creating a stationary magnetic field which applies a static torque to the rotor. This slows and eventually halts the rotor completely.

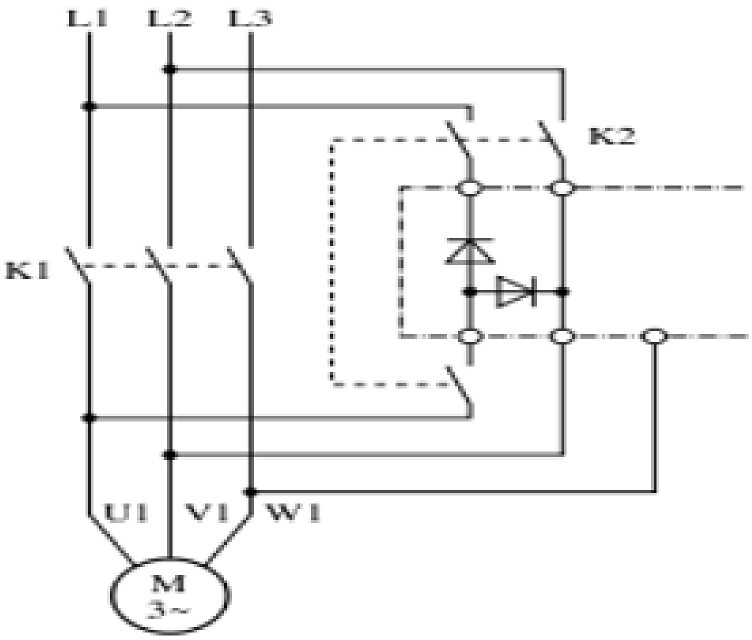


Figure 3.7 – DC injection braking motor
(Sources: El-Sharkawi, 2018)

As long as the DC voltage is applied to the windings, the rotor are going to be held in position and unaffected to any attempt to spin it. The higher the voltage that is applied, the stronger the braking force and holding power.

TOPIC 3 – SUMMARY

[BRAKING OF AC MOTOR]

TOPIC 3 explained further about methods of slowing down an AC motor and induction motor. Electric circuit diagram and graph chart is used to help students understand the methods clearly. Equation derivation and example is given to determine the motor speed and the delivery power.

There are three methods of controlling the induction motor braking that students need to know. Those braking methods are dynamic braking, regenerative braking and DC injection braking. Simple illustration and equations is provided in this chapter to help students understanding.

TIPS & TRICKS

Tips & Tricks

Formula

$$\epsilon = -N\frac{\partial \Phi_B}{\partial t}$$

ϵ = induced emf

N = number of turns in coil

$\partial \Phi_B$ = change in magnetic flux

∂t = change in time

Faraday's Law

Formula

$$\varepsilon = -N\frac{\Delta \Phi}{\Delta t}$$

ε = induced voltage

N = number of loops

$\Delta \Phi$ = change in magnetic flux

Δt = change in time

Lenz's Law

"While Faraday's law tells the magnitude of the EMF that is produced, Lenz's law tells the direction in which the current will flow. The law states that the direction is always such that it will oppose the change in flux that produced it"

(Source : Leverageedu)

1. A 208 V, 60 Hz, 6-pole, 3 phase, Y-connected induction motor has the following parameters:

R_1=0.6 Ω R'_2=0.4 Ω X_{eq}=5 Ω

The motor is loaded by a 30 Nm bidirectional constant torque. If the load torque is reversed, calculate: (i) the motor speed; (ii) the power delivered to the electrical supply (https://www.homeworklib.com/qaa/1669113).

Answer :

(i) The motor speed

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

$$\omega_s = \frac{2\pi ns}{60} = \frac{2\pi(1200)}{60}\ 125.664\ rad/\sec \quad where \quad T_d \approx \frac{V^2{}_s}{\omega_2 R'_2}$$

$$-30 \approx \frac{208^2 s}{125.664\ (0.4)} \quad and\ s = 0.035$$

$$\boldsymbol{Motor\,speed = ns\ (1 - s) = 1200\ (1 + 0.035) = 1242\ rpm}$$

(ii) The power delivered to the electrical supply

$$\omega_s = \frac{2\pi n_s}{60} = \frac{2\pi(1242)}{60} = 130.062\ rad/sec$$

$$P_d = Td\omega = 30\ (130.062) = 3.902\ kW$$

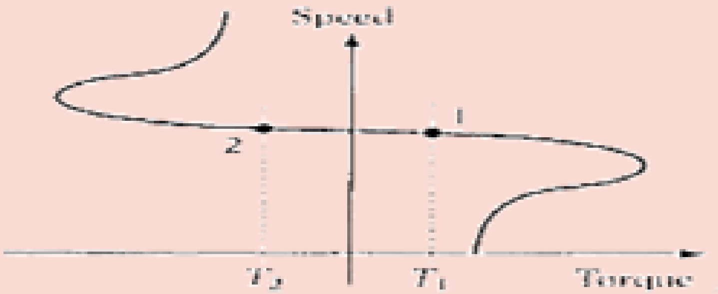
$$P_d = 3(I'_2)^2\,\frac{R'_2}{s}(1 - s)$$

$$-3902 = 3(I'_2)^2\,\frac{0.4}{-0.035}(1 + 0.035) \quad \text{where } I'_2 = 10.486\ A$$

$$P_{loss} = 3\ (1'_2)^2\ (R_1 + R'_2) = 3(10.486)^2 = 330\ W$$

$$\boldsymbol{P_{ds} = Pd - Ploss = 3902 - 330 = 3.572\ kW}$$

2. Discuss the effects of motor speed and torque under regenerative braking method of an induction motor with the aid of speed-torque curve.



Answer : →

- *The reference operating point 1 represents a motor operation where the motor speed is less than the synchronous speed.*
- *When the load torque changes its direction from T1 to T2, the motor operates in second quadrant and the speed of the motor exceeds its synchronous speed.*
- *Keep in mind that that the motor still rotates in its original direction*

3. Describe the regenerative braking of an ac motor.

Answer → :

Regenerative braking occurs when the motor speed exceeds the synchronous speed. This may happen when the load torque drives the electric motor beyond its synchronous speed. In this case, the load is the source of energy and the induction motor is converting the mechanical power into electrical power, which is delivered back to the electrical system.

4. For regenerative braking of an induction motor, which statement below is most suitable for explaining regenerative braking ?

A. synchronous speed should be a little higher than the rotor speed

B. synchronous speed should be a little lower than the rotor speed

C. synchronous speed should be doubled

D. synchronous speed should be increased by a factor of 1.5

Answer → :

synchronous speed should be a little lower than the rotor speed

TOPIC 3 – HOMEWORK

[BRAKING OF AC MOTOR]

1. An induction motor is driven by a six-step converter as shown in Figure 1. The voltage at the DC link, VDC is 200V. At normal full-load operation, the motor current is 25A. The stator resistance is 0.5Ω. The FWM technique is used during dynamic braking. From the information given, express the duty ratio of the FWM (assume that the braking current is three times the rated value).

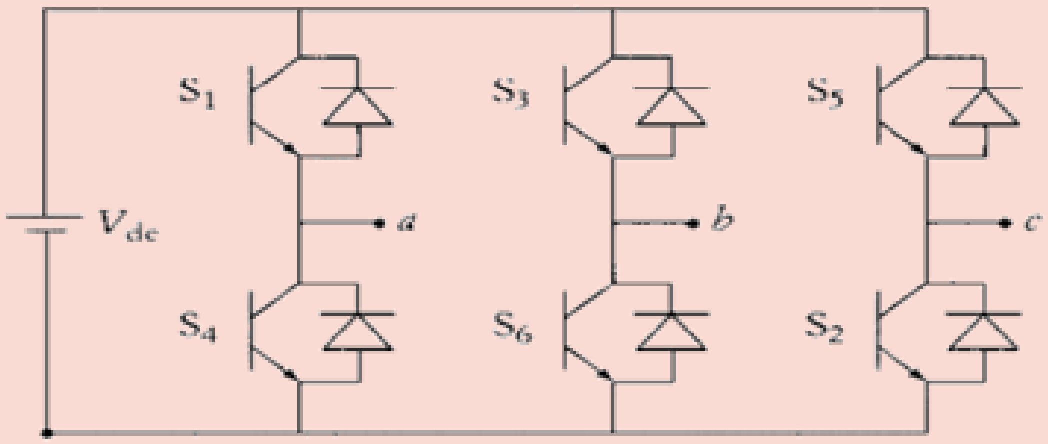


Figure 1

2. With the aid of diagrams, demonstrate and provide an explanation of the methods to slowdown an AC motor using DC Injection Braking.

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