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Title:

Control of Electric Machines

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Higher Degree Research degrees

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This course Support is intended for third-year Electrotechnics students (6th semester)

Table of Contents:

General Introduction

Electric motors are, nowadays, apart from lighting devices, the most numerous receivers in industries and tertiary installations. Their function, which is to convert electrical energy into mechanical energy, gives them a particular economic importance, making them indispensable for any installation or machine designer, installer, or operator.

Many industrial systems driven by electric motors use speed variation to optimize their operation. Since the advent of semiconductor technology, electronic speed control of electric motors has taken precedence over older systems such as Ward-Leonard groups.

This course handout, titled "Control of Machines," is intended for Bachelor's students in Electrical Engineering. It is composed of three parts:

The first chapter presents the structure of an electric drive system and summarizes the mechanical elements that allow for bringing the load characteristics to the motor's axis.

The second part deals with the control of static converters, such as full-wave control, phase-shifted control, and PWM techniques.

The third part is dedicated to the control of direct current motors. It first presents generalities on the characteristics of these machines and then addresses speed control methods.

In the fourth chapter, the main characteristics of the three-phase asynchronous machine are recalled, along with various control techniques for this machine.

The fifth chapter describes the self-controlled synchronous machine and its control methods

This course makes extensive use of various reference books from which I have taken curves or diagrams. I would like to thank all those who directly and/or indirectly contributed to the enrichment of this course.

Chapter I: *Introduction to the Control of Electric Machines*

I.1 Introduction :

In both industry and transportation, there is an increasing need for systems that offer continuously variable speed with flexibility and precision. While mechanical and hydraulic solutions are still in use, electronic solutions have become the most preferred by far. Their success stems from the unparalleled characteristics provided by electronics, both in terms of energy conversion and speed control.

The use of variable-speed drives is partly motivated by the desire to optimize the speed of the driven equipment for each phase of a process. However, it is mainly due to advancements in automation, which require the ability to control the speed of each motor operating at various points within a system. This leads to improved production rates and enhanced product quality. Additionally, advances in power electronics now allow for excellent efficiency by matching power output to the actual demand.

The widespread adoption of variable speed technology aims to achieve significant savings, as "money is the lifeblood of the economy." These savings include

- Energy consumption
- Raw material usage (improving production quality, reducing waste)
- Time utilization (increasing production rates, optimizing machine usage time)

These three areas of savings—energy, raw materials, and time—encapsulate the new field of variable speed application.L’équation qui définit le nouveau domaine d’application de la vitesse variable.

I.2 Structure of an Electric Drive System:

An electric drive is an electromechanical system designed to perform a technological process through the movement of a working component. The control of an electric machine is described by the following structural diagram:

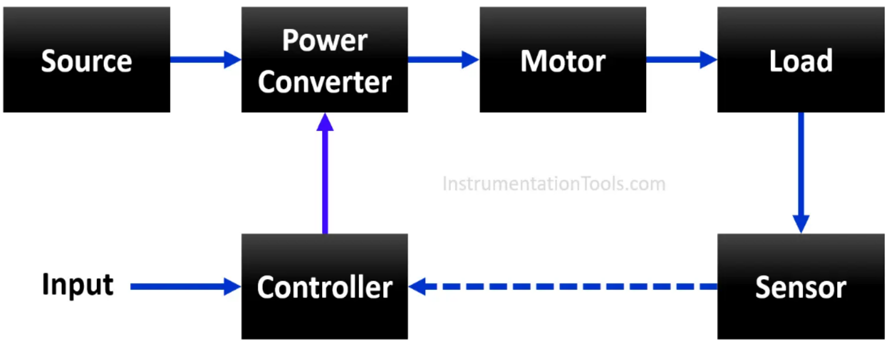


Figure I. 1 **:** Block Diagram of Electrical Drive

Several requirements are imposed on controlled electric machines, among which the following can be distinguished:

Desired Characteristics:

- Power
- Maximum speed and speed adjustment range
- Resistant torque as a function of speed
- Current limitation

Operating Conditions:

- Starting conditions
- Braking and reversibility conditions
- Conditions imposed by the network
- Space requirements
- Investment and operating costs

I.3 Composition of an Electric Drive System

The drive system primarily consists of:

- An electric motor
- A static converter
- A load associated with a mechanical converter
- A control system

1.3.1. Electric Motor :

Electric Motor: This is the essential part for energy conversion (driving machine). It can be a direct current (DC) motor or an alternating current (AC) motor (fig I.2). The motor develops a torque that must be greater than the resisting torque at startup in order to overcome the load. Once the motor starts running, the speed increases (acceleration), as does the electromotive force or induced voltage, causing the absorbed current and the torque developed by the motor to decrease until the torque equals the resisting torque. Consequently, the speed stabilizes and becomes constant. Finally, the acceleration, deceleration, and speed regulation of the motor are controlled by the converter and control system.

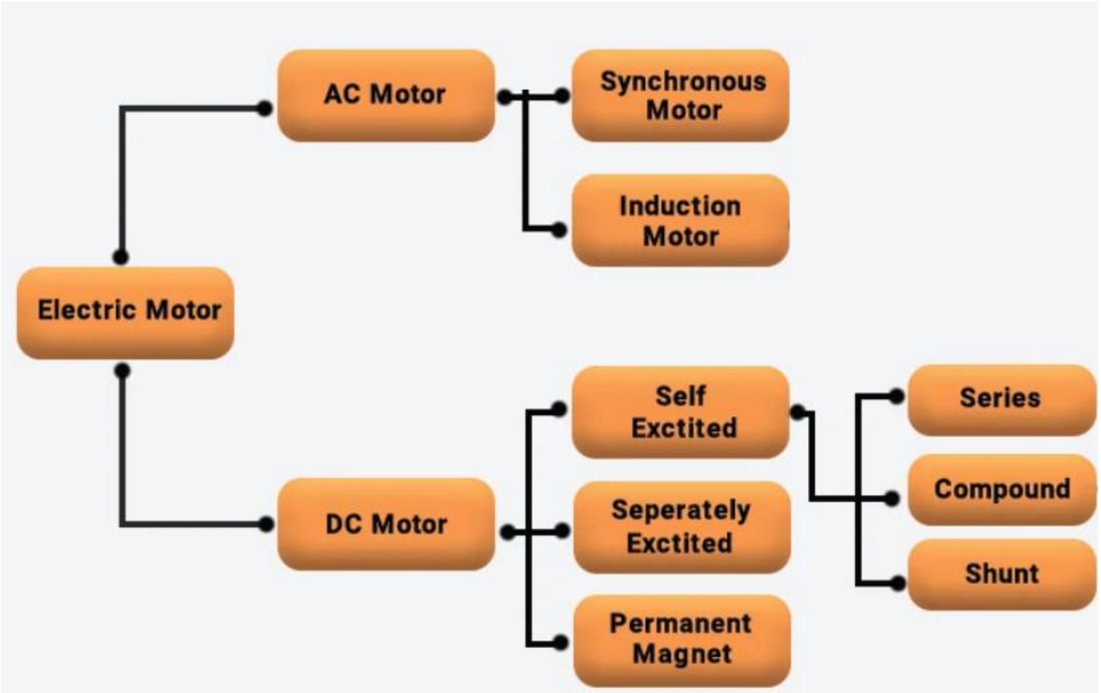


Figure I. 2 : types of electric motor

1.3.2. Static Converter

The static converter transforms electrical energy into the desired form. The converters that are widely used in the field of electric drives are:

- Choppers and rectifiers for direct current (DC) motors
- Phase controllers, cyclo-converters, and inverters for alternating current (AC) motors

1.3.3. Mechanical Converter

Mechanical converters are devices that convert motion. In most industrial applications of electric drives, the load is not driven directly by the motor, either because the required torque is high or because the load involves linear motion.

1.3.4. Load

The load is the element that we want to drive at a given speed. It is characterized by the type of resistance torque it imposes.

- **Constant Torque Loads**: Represented by a horizontal line. This is the case for many machine tools (e.g., drills) and for lifting applications.
- **Torque Proportional to Speed**: This creates a line that passes through the origin. Hydraulic pumps are an example of this type of load.
- **Variable Torque Loads**: The torque is proportional to the square of the speed, resulting in a parabolic curve. Fans are an example of this type of load.

- **Constant Power Loads**: The torque varies inversely with speed, resulting in a hyperbolic curve. This is the case for centrifugation.

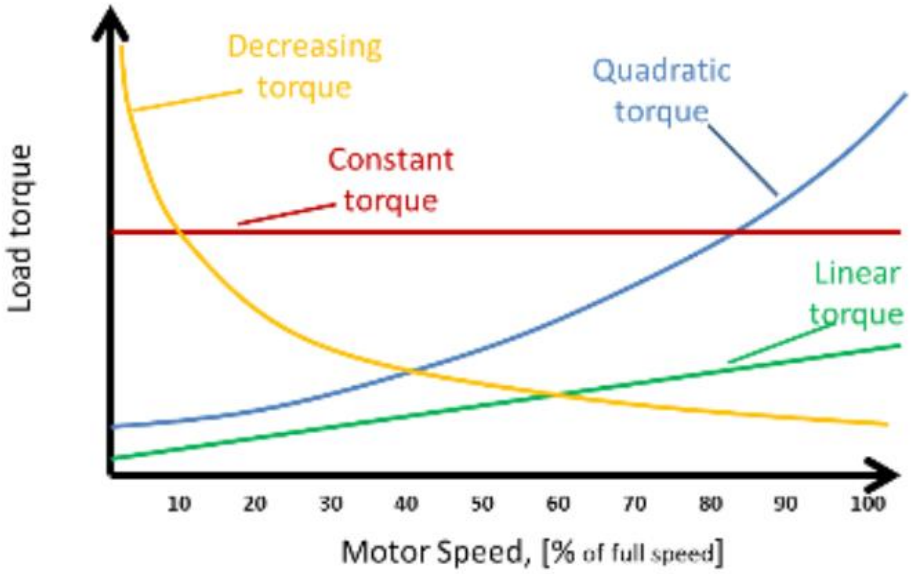


Figure I. 3 : Mechanical characteristics of driven loads

1.3.5. Control System

The control system mainly performs two tasks:

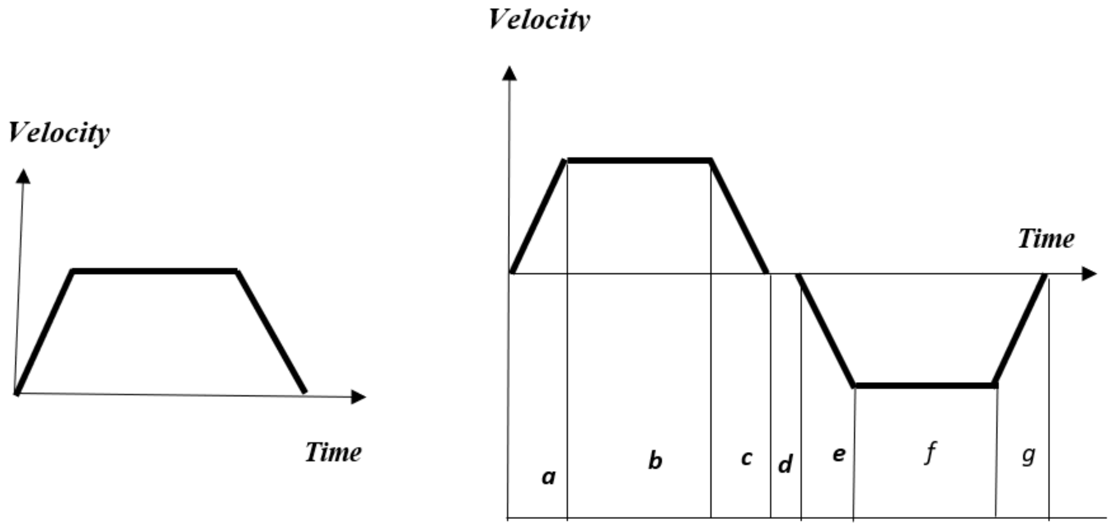
- Limiting and adjusting certain operating parameters (such as flux, current, etc.) to ensure optimal use of the motor-drive system.
- Controlling the regulated variable (such as speed, torque, etc.) in accordance with the desired performance of the drive system.

I.4 Fundamental Concept of a Drive System

1.4.1 Motion profile of a Drive System (Operating Modes)

A motion profile of a drive system refers to the planned or controlled movement of the system's load over time. It outlines how speed, position, and acceleration change during different phases of operation. The motion profile is critical in designing and controlling the drive system to ensure smooth, efficient, and precise operation.

This subsection would discuss the various modes in which an electric drive system can operate (figure I.4). These modes could include:



(1) (2)

Figure I. 4 : Motion profile

- **Start-up Mode:** How the system initiates motion from a standstill, including the strategies used to manage inrush current and torque.
- **Continuous Operation Mode:** The system's behavior during normal, steady-state operation, where speed and torque are maintained according to the load demand.
- **Acceleration and Deceleration Modes:** The control of speed increase or decrease, ensuring smooth transitions and avoiding mechanical or electrical stress.
- **Braking Mode:** How the system slows down or stops, which could involve regenerative braking, dynamic braking, or other methods.
- **Dwell Time:**In some applications, the system may need to hold its position or maintain a specific speed for a period before the next phase of motion.
  Dwell time is important in applications requiring precise positioning or timing.
- **Reversing Mode:** The capability of the system to change the direction of rotation, particularly in applications requiring bidirectional control.

Each mode would be tailored to meet specific requirements of the application, ensuring efficiency, safety, and reliability of the drive

1.4.2. Quadrants de fonctionnement

In the context of electric drive systems, the "quadrants of operation" refer to the different modes in which the system can operate based on the direction of rotation (speed) and the direction of torque (force). These quadrants are typically represented in a coordinate system where the x-axis represents speed and the y-axis represents torque. There are four quadrants, each corresponding to a specific combination of speed and torque direction.

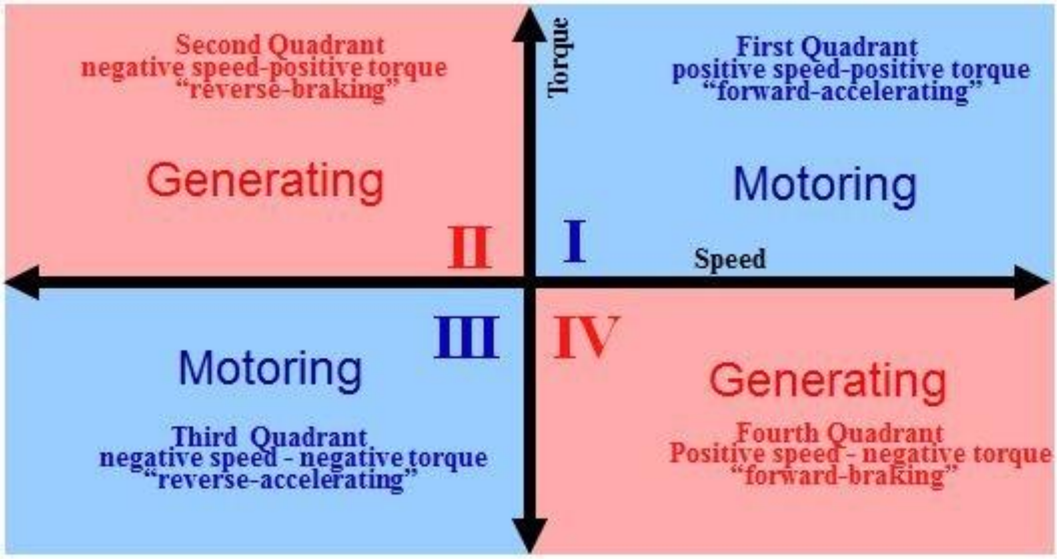


Figure I. 5 : Four Quadrant Operation of Motor Drive

First Quadrant (Forward Motoring)

- **Speed:** Positive (Forward)
- **Torque:** Positive (Driving Torque)
- **Operation:** In this quadrant, the motor operates in a typical forward direction, driving the load with a positive torque. This is the most common operating mode for many applications, such as driving a vehicle forward or operating a conveyor belt in its standard direction. The motor consumes electrical energy and converts it into mechanical energy to move the load.

Second Quadrant (Forward Braking or Regenerative Braking)

- **Speed:** Positive (Forward)
- **Torque:** Negative (Braking Torque)
- **Operation:** Here, the motor is still rotating in the forward direction, but the torque is negative. This means that the motor is acting as a brake, decelerating the load. This often occurs during regenerative braking, where the kinetic energy of the load is converted back into electrical energy, which can be fed back into the power supply or dissipated through resistors. This mode is useful in applications like electric vehicles, where energy recovery is important.

Third Quadrant (Reverse Motoring)

- **Speed:** Negative (Reverse)
- **Torque:** Negative (Driving Torque)

- **Operation:** In this quadrant, the motor operates in reverse, driving the load backward with negative torque. The motor again consumes electrical energy, converting it into mechanical energy, but in the opposite direction. This mode is used when the system needs to move in reverse, such as backing up a vehicle or reversing the direction of a conveyor belt.

Fourth Quadrant (Reverse Braking or Regenerative Braking)

- **Speed:** Negative (Reverse)
- **Torque:** Positive (Braking Torque)
- **Operation:** The motor is rotating in the reverse direction, but with a positive torque, meaning it is decelerating the reverse motion. Similar to the second quadrant, this is also a braking mode where the motor acts to slow down the load, potentially recovering energy. This mode is useful in reversing operations where controlled deceleration is required.

Importance of Understanding the Quadrants

Understanding the quadrants of operation is crucial for designing and controlling electric drive systems, especially when precise control over motion and energy efficiency is required. Different quadrants are utilized depending on the application, and they have implications for the control strategy, energy consumption, and wear on the system components.

- **Energy Management:** Regenerative braking (second and fourth quadrants) allows for energy recovery, improving overall system efficiency.
- **Control Complexity:** Systems that operate in multiple quadrants require more complex control algorithms to manage transitions smoothly.
- **Application Suitability:** Some motors and drive systems are better suited for specific quadrants, influencing the choice of equipment for a particular application.

The quadrants of operation provide a framework for understanding and managing the different modes in which an electric drive system can operate, helping to optimize performance, energy use, and system longevity.

1.4.3. Operating Point

The operating point, also known as the "point de fonctionnement" in French, refers to the specific conditions under which an electric drive system operates at a given moment. It is defined by the intersection of the motor's characteristic curve ($\boldsymbol{T_m} = f(\Omega)$) with the load's characteristic curve ($\boldsymbol{T_r} = f(\Omega)$), indicating the balance between the motor's output and the load's demand.

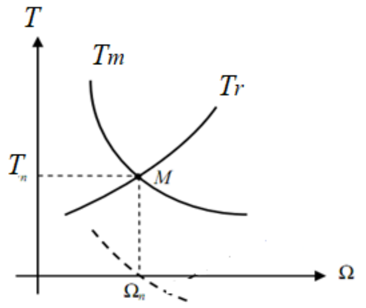


Figure I. 6 : Operating Point

1.4.4. Stability of the Operating Point:

The most critical step is to determine whether the operating point is stable or unstable; this involves evaluating whether the system is in a state of stable or unstable equilibrium.

Let's recall the fundamental relationship of dynamics:

$\boldsymbol{T_m - T_r = J\frac{d\Omega}{dt}}$ where J is the moment of inertia of the system.

- **At the operating point, we have**: $\boldsymbol{T_m = T_r}$
- **Stable Regime: :**

Consider Figure I.5 and suppose that, due to some external cause (such as friction from a hand on the shaft), the speed of the system decreases Ω↘. We notice that the motor torque then becomes greater than the resisting torque ($\boldsymbol{T_m - T_r} > 0$), resulting in $\boldsymbol{\frac{d\Omega}{dt}} > 0$, which will produce an **acceleration** and bring the system back to its initial speed.

Conversely, if we act to increase the speed of the system, the resisting torque would become greater than the motor torque ($\boldsymbol{T_m - T_r} < 0$), resulting in $\boldsymbol{\frac{d\Omega}{dt}} < 0$, and the internal action would tend to oppose this effect, bringing the system back to its initial speed.

- **Unstable régime:**

We can show that the system in Figure I.7 is unstable:

- A decrease in speed leads to $\boldsymbol{T_m - T_r} < 0$, meaning that $\boldsymbol{\frac{d\Omega}{dt}} < 0$, which worsens the deceleration until the motor stalls.
- An increase in speed leads to $\boldsymbol{T_m - T_r} > 0$, meaning that $\boldsymbol{\frac{d\Omega}{dt}} > 0$, which worsens the acceleration until the motor runs away.

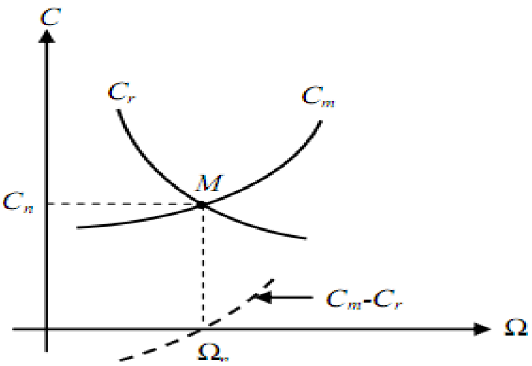


Figure I. 7 : : Unstable operation of a motor-driven load system.

The condition for stability can be expressed as follows: For the operating point to be stable, it is necessary and sufficient that the slope of the resisting torque with respect to speed be greater than the slope of the motor torque with respect to speed.

Chapter II:

Control of Static Converters

II.1 Introduction :

In modern industrial applications, the need for precise and efficient control of motor operations is paramount. This is where static converters come into play. Static converters, based on advanced semiconductor technology, have revolutionized motor control

Unlike traditional methods that relied on mechanical or hydraulic systems, static converters allow for seamless and rapid adjustments of motor speed, torque, and direction. They achieve this by converting electrical energy from one form to another, enabling the motor to operate optimally under varying load conditions. Whether it's for accelerating a motor to a specific speed, maintaining that speed under load, or decelerating it with precision, static converters offer a level of control that was previously unattainable.

II.2 Advantages to the Use of Static Converters in Motor Control:

Converters offer several key advantages in the control of electric machines, particularly when compared to traditional mechanical, hydraulic, and electrical systems:

- ✓ **Rapid Response Time:** Electronic circuits, especially those based on power semiconductors, have significantly faster response times. While a high-quality electrical relay may respond in milliseconds and a hydraulic system in a few hundredths of a second, electronic systems are vastly quicker, with response times that are a hundred thousand times faster than the fastest alternatives.
- ✓ **Flexibility:** Converters allow for precise control over machine operation, enabling adjustments to speed, torque, and other parameters with high accuracy.
- ✓ **Compactness:** Electronic systems are typically more compact than mechanical or hydraulic systems, saving space and allowing for more efficient use of resources.
- ✓ **Noise Reduction:** Converters often operate more quietly than mechanical or hydraulic systems, contributing to a quieter working environment.
- ✓ **Efficiency:** The use of electronic converters can lead to improved energy efficiency, as they are capable of fine-tuning power usage to match the exact needs of the application.
- ✓ **Cost-Effectiveness:** Over time, the reliability, lower maintenance requirements, and efficiency of electronic converters can lead to cost savings in both operation and maintenance.
- ✓ **Reliability and Safety:** Modern electronic systems are highly reliable and can incorporate advanced safety features, reducing the likelihood of failures and enhancing overall system security.

These advantages make converters the preferred choice for controlling electric machines, especially in applications requiring variable speed and precise control.

II.3 Different Control Strategies of Converters:

An inverter is composed of six transistors, each with an antiparallel diode.

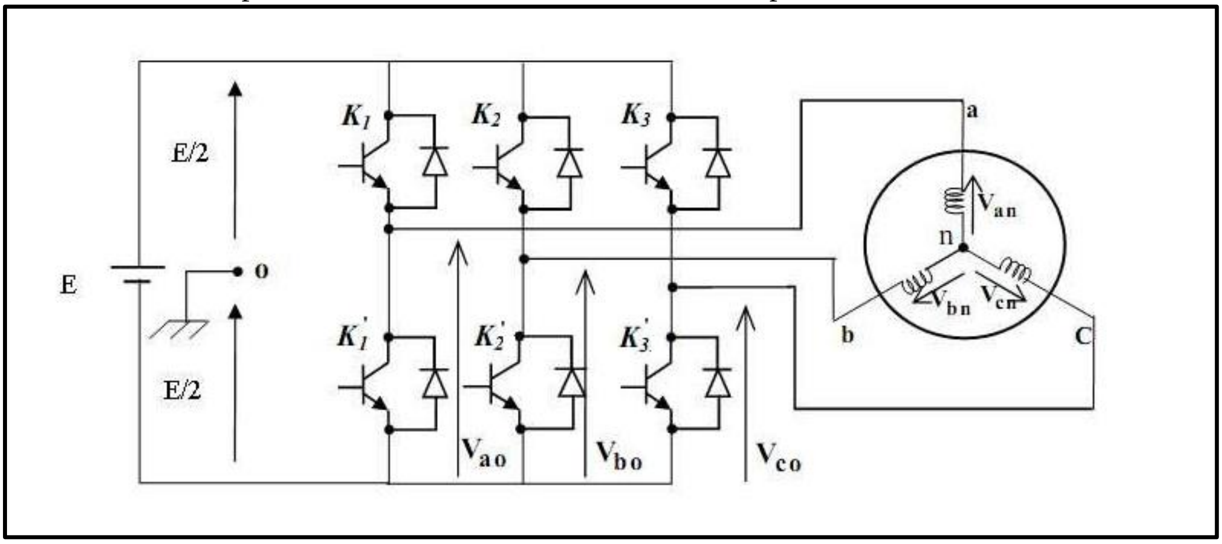


Figure. II. 1: Principal diagram of a 3-Phase inverter.

These components work together to convert DC (direct current) into AC (alternating current) with the desired frequency and amplitude. The control of these transistors is crucial for achieving the correct output and involves several strategies:

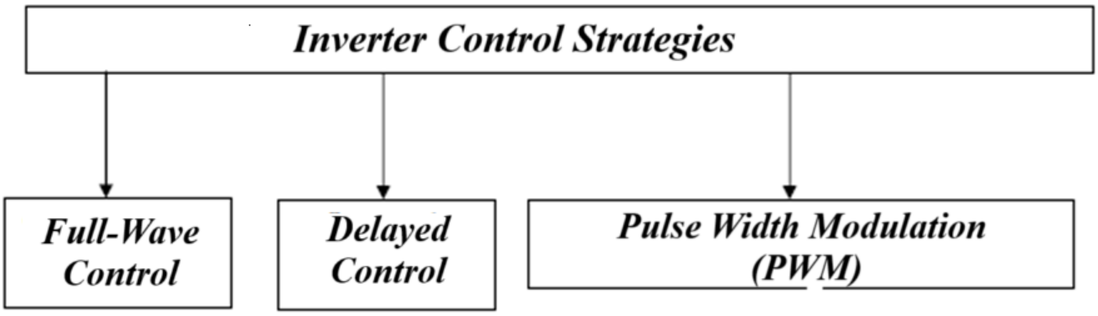


Figure. II. 2: Inverter Control Strategies.

II.3.1 Full-Wave Control: Square Wave Inverter

The square wave inverter is a type of full-wave control device used to convert DC power into AC power, generating a square wave output instead of the traditional sinusoidal wave. This method of control is commonly employed in simpler and cost-effective inverter designs for powering AC loads from a DC source.

To illustrate the operation of an inverter, it is beneficial to study its behavior under full-wave control (180°). This mode of operation provides a clearer understanding of other control strategies. This method is also known as six-step control.

In this type of control, the sequence of closing a switch coincides with the opening of the switch located on the same leg of the inverter. For the first leg of the inverter, the switch K_a remains closed for half a period (180°), while K'_a is closed during the other half-period. The same procedure is applied to the other two legs of the inverter but with phase shifts of $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$ relative to the first leg.

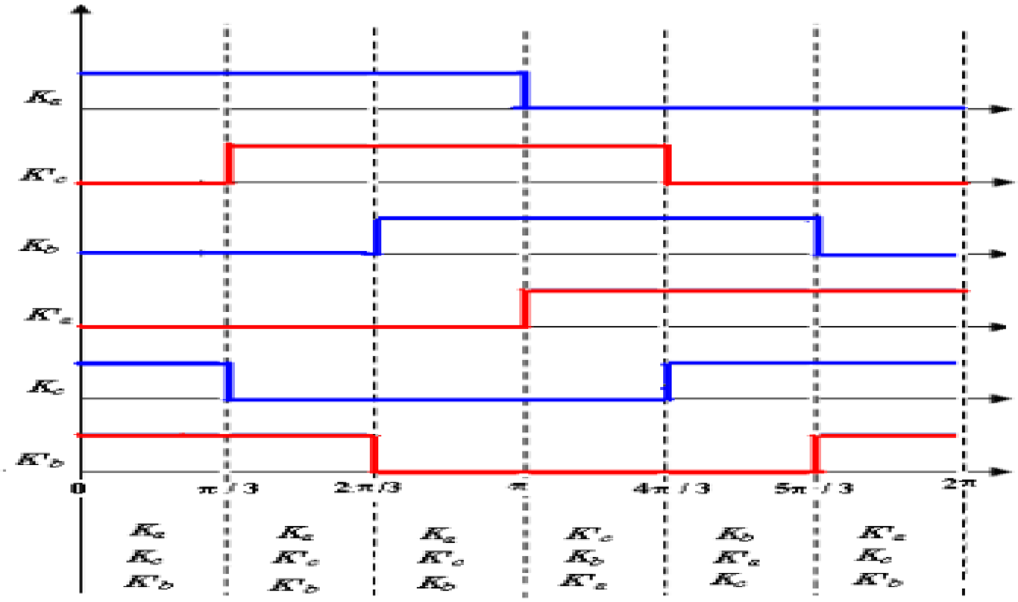


Figure. II. 3: waveforms input by a 3-phase square wave (180°)

Voltage waveforms output by a 3-phase square wave in figure II.4.

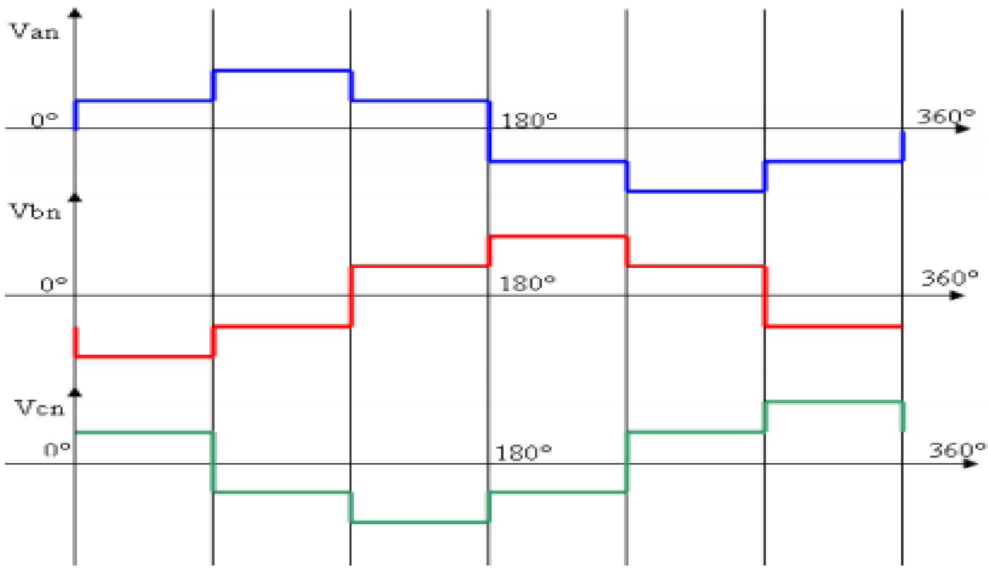


Figure. II. 4: Voltage waveforms output by a 3-phase square wave (180°)

The inverter produces rectangular or square wave voltages, and when analyzed using Fourier series decomposition, it shows a significant presence of harmonics, with the absence of harmonics that are multiples of 3. The output voltages of the inverter include harmonics such as the 5th, 7th, and 11th, which are close to the fundamental frequency. Among these, the 5th harmonic has a particularly high amplitude (see Figure II.5).

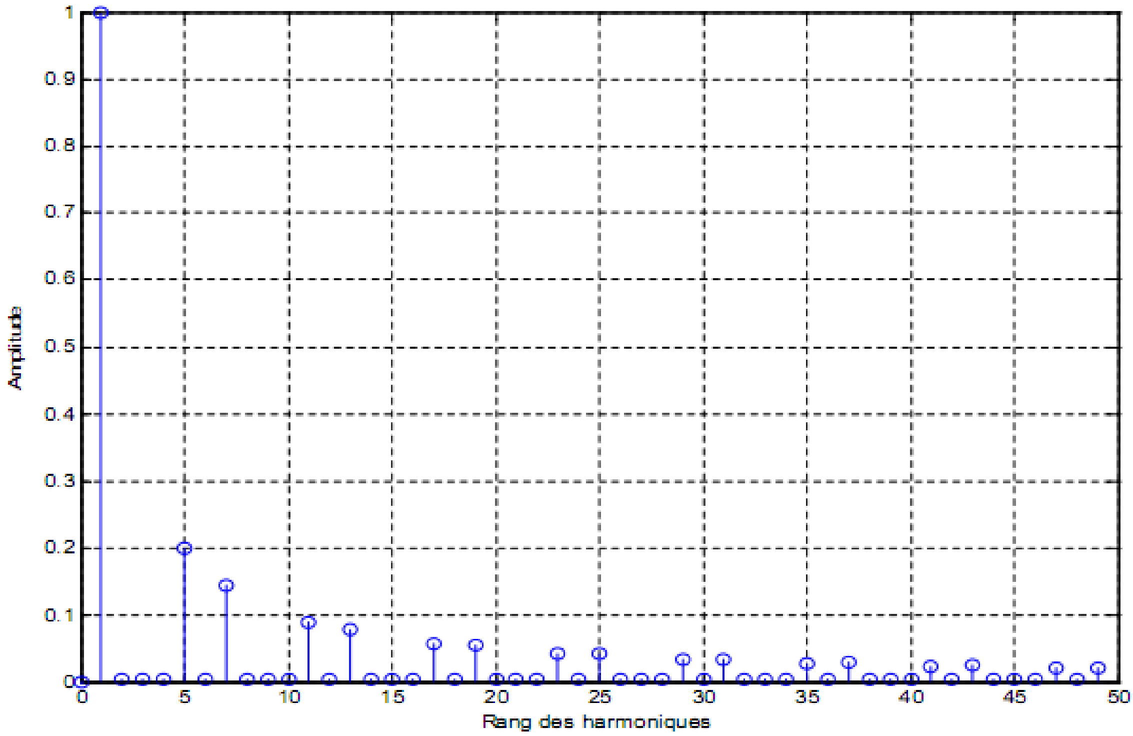


Figure. II. 5: Harmonic Analysis of a Three-Level Square-Wave Inverter's Voltage.

Advantages and Limitations:

Advantages:

Cost-effective, simple design, efficient in converting DC to AC power.

Common applications include powering basic AC devices, emergency power systems, and in some motor control scenarios where the simplicity and cost-effectiveness of the inverter are prioritized.

Limitations:

High harmonic content, not suitable for sensitive electronics or high-precision applications.

Harmonics and Filtering: One of the main drawbacks of square wave inverters is the generation of higher harmonic content compared to sinusoidal inverters. These harmonics can cause additional heating and reduced efficiency in inductive loads such as motors.

To mitigate the effects of harmonics, filtering circuits may be added, but this increases the complexity and cost of the system.

II.3.2 Delayed Command of an Inverter (120°) :

In a delayed command strategy for an inverter, also known as phase-shifted or staggered control, the switching of transistors is not simultaneous but occurs with a deliberate time delay.

In phase-shifted control (120°), the switches are operated for a duration corresponding to one-third of the period, but with sequences shifted by 120° between phases.

In this strategy, the closing command for one switch no longer coincides with the opening command of the switch on the same leg.

Figure II.6 illustrates the output voltages of the inverter with phase-shifted control. The waveforms show that the three phase voltages have alternating positive and negative rectangular shapes. The phase shift between each pair of voltages is 120°.

This technique eliminates the issue of **short-circuits** within the inverter. However, harmonic distortion remains a concern.

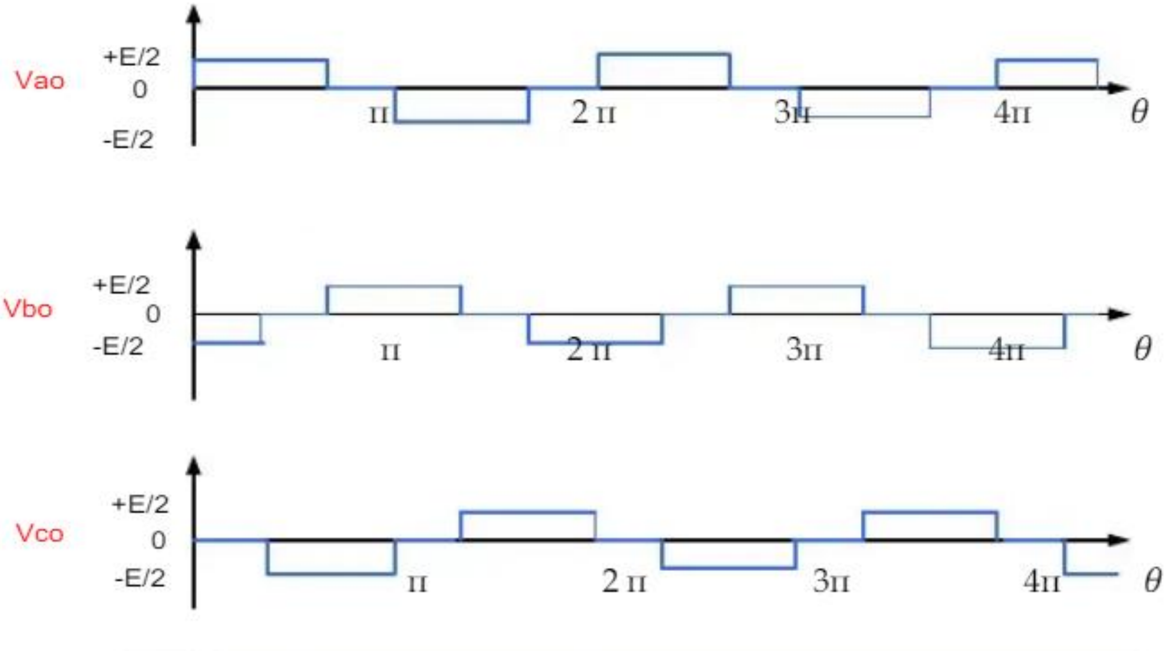


Figure. II. 6: The phase voltages of the inverter with 120° control.

Advantages of 120° Control:

1. **Simplicity**: The 120° control strategy is simpler to implement compared to other control methods.
2. **Short-Circuit Elimination**: This control method effectively eliminates the risk of short-circuits within the inverter by ensuring that the switching sequences are appropriately timed.

Disadvantages of 120° Control:

1. **High Harmonic Content**: The output voltage is rich in low-order harmonics, which can cause distortion and reduce the quality of the power delivered to the load.
2. **Filtering Requirements**: Due to the high harmonic content, filtering the output voltage or current is challenging and expensive. The first harmonic that needs to be filtered out has a frequency very close to the fundamental frequency, making it difficult to achieve effective filtering without significant cost.

II.3.3 Pulse Width Modulation (PWM):

Pulse Width Modulation (PWM) is a widely used technique in the control of inverters. The basic idea of PWM is to modulate the width of the pulses in the inverter's output voltage to control the effective voltage and current delivered to the load.

II.3.3.1 Generation of the PWM Signal:

A pulse width modulating signal is generated using a comparator. The modulating signal forms one part of the input to the comparator, while the non-sinusoidal wave or sawtooth wave forms the other part of the input. The comparator compares two signals and generates a PWM signal as its output waveform.

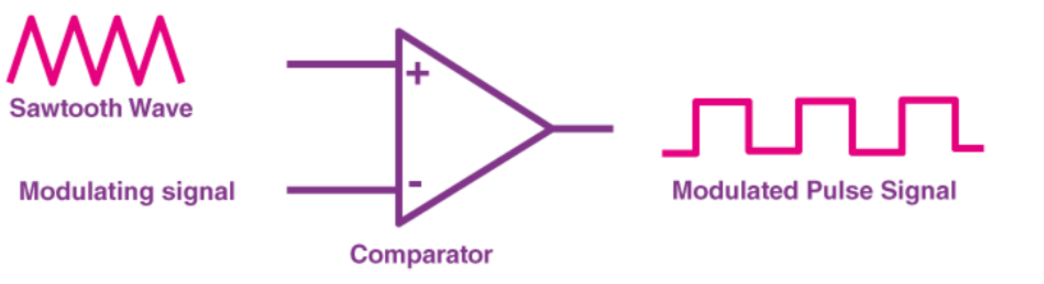


Figure. II. 7: The principle of Pulse Width Modulation (PWM)

If the sawtooth signal is more than the modulating signal, then the output signal is in a “High” state. The value of the magnitude determines the comparator output which defines the width of the pulse generated at the output.

- **Duty Cycle of PWM**

In PWM, the inverter switches on and off at a high frequency, and by adjusting the ratio of on-time to off-time (known as the duty cycle), it can effectively control the average voltage seen by the load.

$$Duty\ Cycle = \frac{Turn\ On\ Time}{Turn\ On\ Time + Turn\ Off\ Time} \quad (II.1)$$

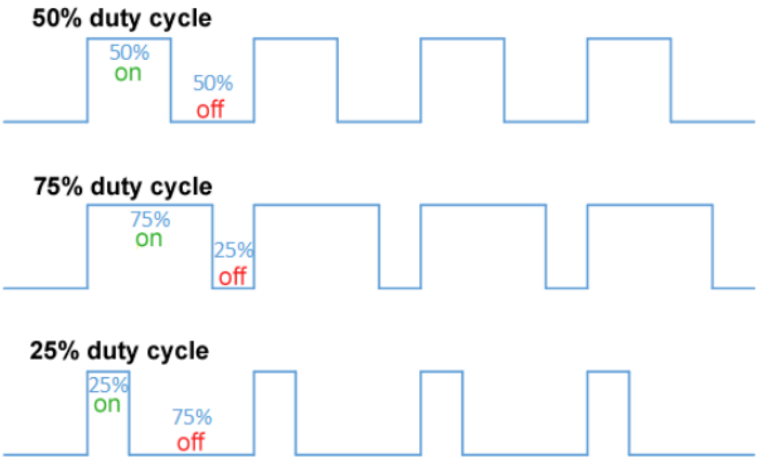


Figure. II. 8: Duty cycle.

- Frequency of PWM The frequency of PWM determines how fast a PWM completes a period. The frequency of a pulse is shown in the figure II.9 .

The frequency of PWM can be calculated as follows:

Frequency = 1/Time Period

Time Period = On Time + OFF time

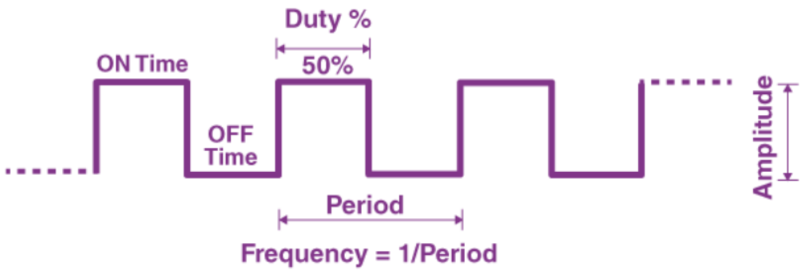


Figure. II. 9: The frequency of a pulse.

II.3.3.2 Sinusoidal-Triangle PWM:

The Sinusoidal-Triangle PWM method is one of the most commonly used techniques for generating a PWM signal, especially in the control of inverters.

- **Carrier and Reference Signals:** The technique involves comparing a sinusoidal reference signal (which represents the desired output waveform) with a high-frequency triangular carrier signal.
- **Pulse Generation:** Whenever the sinusoidal reference signal is greater than the triangular carrier signal, a pulse is generated. The width of this pulse corresponds to the duration where the reference signal exceeds the carrier.

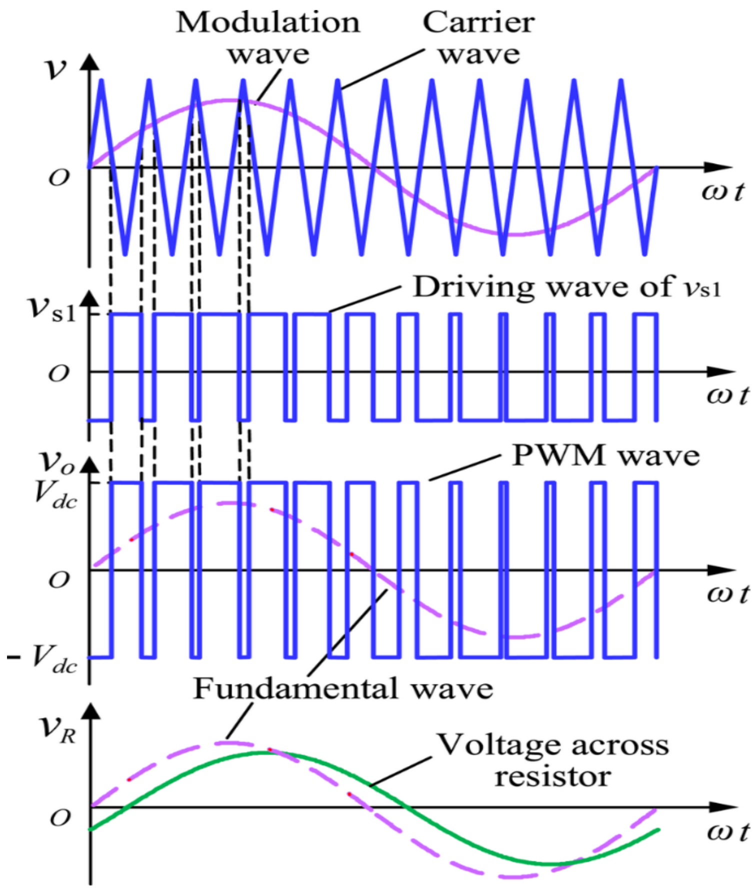


Figure. II. 10: PWM waveform generation and voltage across resistor. PWM, pulse width modulation

II.3.3.2.1 Properties:

This technique is characterized by two key parameters:

- **Frequency modulation index :**

The modulation index 'm' is defined as the ratio of the carrier frequency (f_{tri}) to the reference frequency (f_{ref}):

$$m_f = \frac{f_{tri}}{f_{ref}} \quad (II.2)$$

A higher modulation index 'm' improves the suppression of harmonics, leading to a cleaner output waveform.

- **Amplitude modulation index**

The amplitude mplitude modulation index reflects the ratio of the reference voltage amplitude (V_{ref}) to the carrier voltage amplitude (V_{tri}):

$$m_a = \frac{V_{ref}}{V_{tri}} \quad (II.3)$$

The goal is to achieve the highest possible value of 'ma' for optimal voltage control.

II.3.3.2.2 Considerations:

- ✓ **Harmonic Suppression:** As the modulation index 'mf' increases, the technique becomes more effective at reducing harmonics in the output waveform, leading to better performance.
- ✓ **Switching Losses:** However, when choosing 'm', it's important to consider the additional losses that occur during the transitions between states. These losses increase as the modulation frequency rises.
- ✓ **Operational Constraints:** The system can never operate with a modulation ratio 'ma' equal to 1 because it's essential to leave enough time for the conduction and blocking intervals of the switches within the same inverter leg.

II.3.3.2.3 Advantages and Disadvantages of PWM:

Advantages of PWM

- ✓ **Pushing harmonics of the output voltage to higher frequencies**, which simplifies filtering (easier implementation, lower cost).
- ✓ **Improved Harmonic Performance:** PWM significantly reduces the harmonic content in the output voltage, resulting in a cleaner and more sinusoidal waveform, which improves the performance of the motor.
- ✓ **Higher Efficiency:** By precisely controlling the output voltage, PWM can improve the efficiency of the motor and reduce energy losses.
- ✓ **Better Torque Control:** PWM allows for more precise control over the motor's torque, which is essential in applications requiring fine motor control.

Disadvantages of PWM:

- ✓ **Complexity:** Implementing PWM is more complex than simpler control methods like 120° control. It requires more sophisticated electronics and control algorithms.
- ✓ **Switching Losses:** The high-frequency switching in PWM can result in increased switching losses in the inverter, which can lead to higher heat generation and the need for better thermal management.
- ✓ **Electromagnetic Interference (EMI):** The high-frequency switching can also generate electromagnetic interference, which may require additional filtering and shielding to mitigate.

Chapter III:

Speed Control of Direct Current (DC) Machines

III.1 Introduction :

DC motors have long been integral to applications requiring precise speed control and high performance. Their ability to provide a high starting torque, along with a simple and cost-effective speed control mechanism, makes them an ideal choice for many variable-speed drives. Unlike AC motors, DC motors can easily adjust speed over a wide range by simply varying the voltage applied to the armature or adjusting the field current.

Historically, DC motors have been preferred for applications demanding very high speeds or precise speed control, such as in industrial machinery, electric vehicles, and robotics. This preference is due to the direct relationship between voltage and speed in DC motors, which allows for straightforward and efficient control. Additionally, these motors offer excellent speed regulation under varying load conditions, making them highly reliable for tasks where consistent speed is crucial.

However, despite their advantages, DC motors have some limitations. The use of a commutator and brushes, essential components for the operation of DC motors, introduces mechanical wear and tear, leading to higher maintenance requirements. These components also make DC motors less suitable for environments where they might be exposed to dust, moisture, or chemicals, which could damage the brushes and commutator over time.

As technology has advanced, the development of power electronics and control systems has allowed AC motors to increasingly replace DC motors in many applications. Nevertheless, the simplicity, ease of control, and established technology behind DC motors continue to make them a vital part of many industries, particularly where precise speed control is paramount.

This chapter will delve into the various methods of speed control for DC motors, exploring techniques. By understanding these methods, we can better appreciate the enduring relevance of DC motors in an ever-evolving technological landscape.

III.2 Basic Characteristics of DC Motors:

The equivalent electrical circuit of a separately excited DC motor represents the electrical components of the motor using resistances and inductances. This schematic helps to analyze and understand the motor's behavior based on the applied voltages and currents (figure III.1).

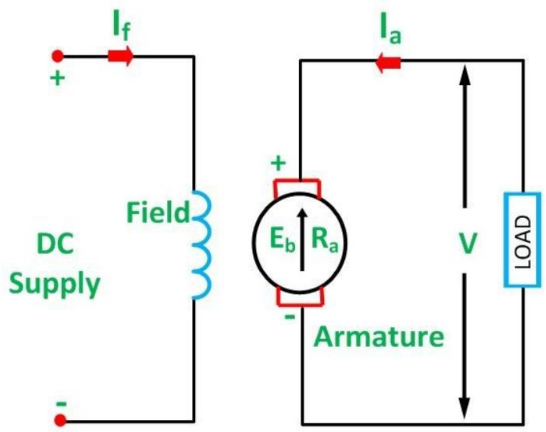


Figure. III. 1: Separately Excited DC Motor.

The electrical equations for the field winding (inductor) and the armature winding (induced) of a DC motor can be expressed as follows:

$$U_e = R_e I_e + L_e \frac{dI_e}{dt} \quad \text{(III. 1)}$$

$$U_a = R_a I_a + L_a \frac{dI_a}{dt} + E \quad \text{(III. 2)}$$

Where **E** is the back electromotive force (back EMF) generated by the motor's armature:

$$E = \frac{PN}{2\pi a} \cdot \Omega \ \cdot \phi \quad (volts) \quad \text{(III. 3)}$$

Here :

p: Number of pole pairs in the inductor;

a : Number of parallel paths in the armature winding;

N: Total number of active armature conductors;

ϕ : Useful magnetic flux per pole (Weber);

Ω: Angular velocity (rad/s).

The factor $\frac{PN}{2\pi a}$ is a constant. Let's denote this constant as :$\frac{PN}{2\pi a} = k$; so:

$$E = k \cdot \Omega \cdot \phi \quad \text{(III. 4)}$$

The relationship between the excitation current and the flux ϕ, and consequently the back EMF, is nonlinear due to magnetic saturation (as illustrated in Figure III.2).

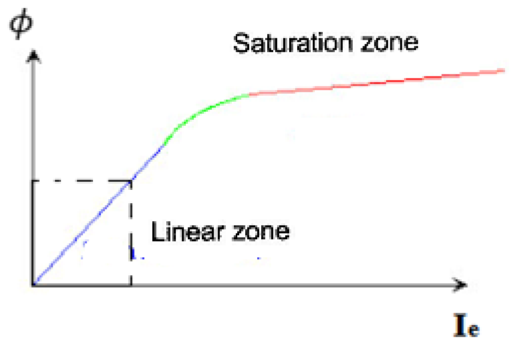


Figure. III. 2: flux curve

If we work in the linear region, where the magnetic flux (ϕ) is proportional to the excitation current I_e , then we have the following:

$$E = k_v \cdot \Omega \cdot I_e \quad \text{(III. 5)}$$

The expression for the electromagnetic torque is given by the relation:

$$T_{em} = k \cdot \phi \cdot I_a \quad = \quad k_v I_e I_a \quad \text{(III. 6)}$$

In steady-state conditions, time derivatives are zero, and the electrical equations of the field winding and armature become:

$$U_e = R_e I_e \quad \text{(III. 7)}$$

$$U_a = R_a I_a + E \quad = \quad R_a I_a + k_v \cdot \Omega \cdot I_e \quad \text{(III. 8)}$$

From the electrical equation of the armature, we can derive the angular speed of a separately excited motor:

$$\Omega = \frac{U_a - R_a I_a}{k_v \cdot I_e} \quad \text{(III. 9)}$$

$$\Omega = \frac{U_a - R_a I_a}{k_v \cdot \frac{U_e}{R_e}} \quad \text{(III. 10)}$$

$$\Omega = \frac{U_a - R_a I_a}{k \cdot \phi} \quad \text{(III. 11)}$$

By exploring these relations, it is clear that there are three main methods of controlling the speed of a d.c. motor, namely:

(i) By varying the applied voltage $\boldsymbol{U_a}$. This is known as **voltage control** method.

(ii) By varying the flux per pole $\boldsymbol{\phi}$. This is known as **flux control** method.

(iii) By varying the resistance in the armature circuit $\boldsymbol{R_a}$. This is known as **armature control** method.

III.3 Speed Variation

III.3.1 Voltage Control

When the field excitation is kept constant at its nominal value, the magnetic flux remains unchanged. In this case, the speed can be varied from zero to the nominal value by adjusting the armature supply voltage U_a from 0 to its nominal value.

Within this range, the motor is capable of delivering its nominal torque Tn at any speed, without experiencing excessive heating. The power P increases proportionally with the speed until both the voltage and the speed reach their nominal values. This is known as the **constant torque operating zone** (Figure III.3). Most industrial applications function in this operating regime.

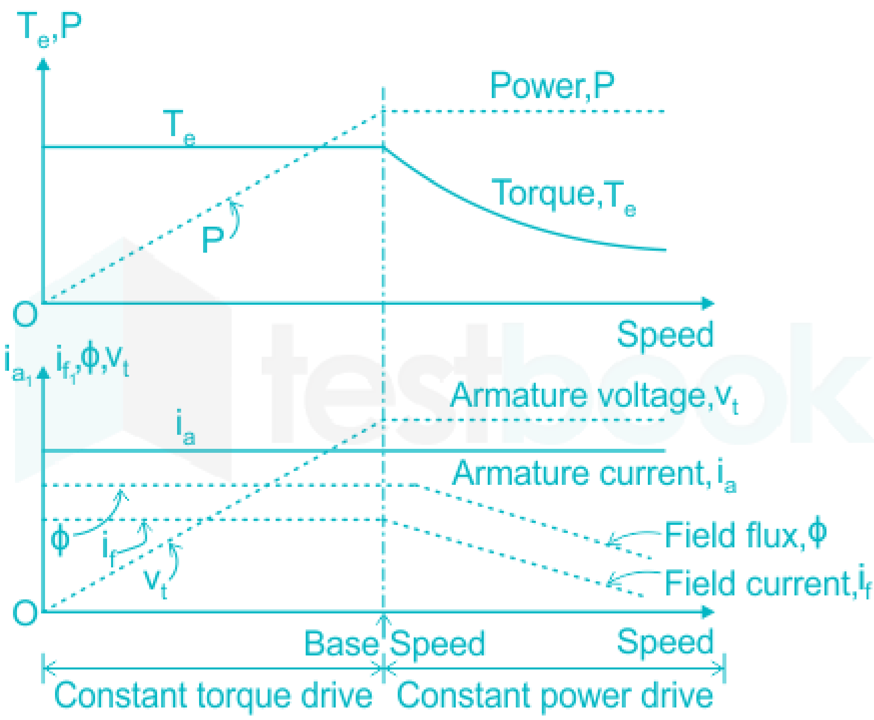


Figure. III. 3: Torque-speed characteristics during constant torque and constant power.

III.3.1.1 The Mechanical Characteristic of Armature Voltage Control:

The angular speed is given by the equation:

$$\Omega = \frac{U_a - R_a I_a}{k\cdot\phi} \Rightarrow I_a = \frac{U_a - k\cdot\phi\cdot\Omega}{R_a} \quad \text{(III. 12)}$$

Substituting the expression for the armature current I_a into the torque equation:

$$T_{em} = k\cdot\phi\cdot I_a = k\cdot\phi\cdot\frac{U_a - k\cdot\phi\cdot\Omega}{R_a} \quad \text{(III. 13)}$$

Simplifying the equation, we get:

$$T_{em} = \frac{k\cdot\phi}{R_a}U_a - \frac{(k\cdot\phi)^2}{R_a}\Omega \quad \text{(III. 14)}$$

Figure III.4 represents the mechanical characteristic $T_{em} = f(\Omega)$, which shows the relationship between the electromagnetic torque and the angular speed at a constant flux and a constant armature voltage U_a.

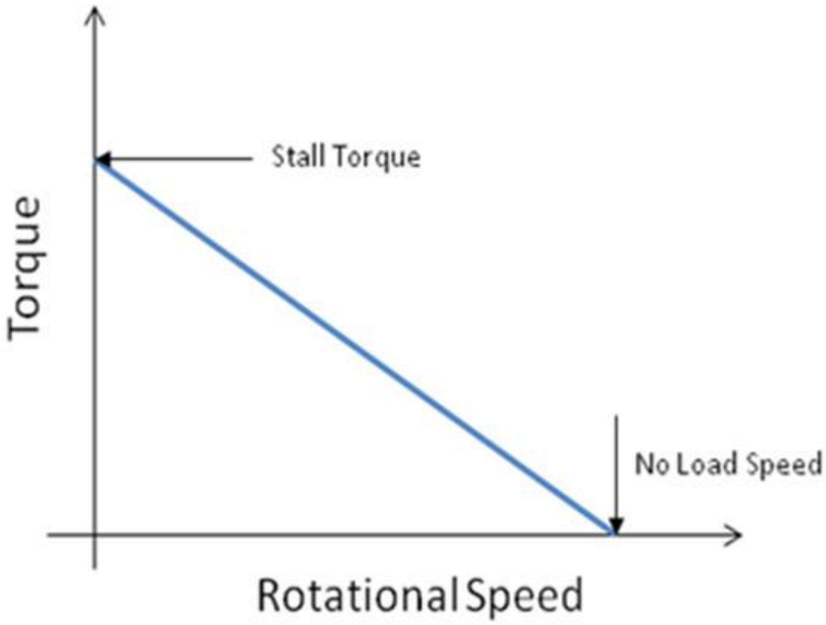


Figure. III. 4: the mechanical characteristic

Based on the following relationships

$$\begin{cases} T_{em} = \grave{K} \cdot I_a \\ \Omega = \frac{U_a - R_a I_a}{\grave{K}} \end{cases} \quad \text{(III. 15)}$$

- For $T_{em} = 0$, we have $I_a = 0 \Rightarrow \Omega = \frac{U_a}{\grave{K}}$. When the armature voltage Ua is reduced, the speed decreases.
- For $\Omega = 0$, we get: $I_a = \frac{U_a}{R_a} \Rightarrow T_{em} = \grave{K} \cdot \frac{U_a}{R_a}$

The mechanical characteristic in the case of armature voltage control is illustrated in Figure III.5.

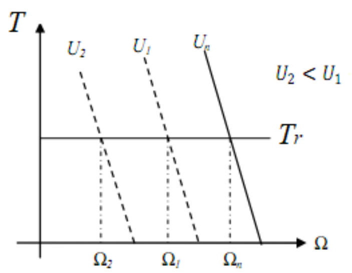


Figure. III. 5: Mechanical characteristic for voltage control.

- The mechanical characteristic shifts parallel to itself.
- The maximum torque is maintained.

This mode of control is technically excellent because the characteristics remain undistorted. Economically, it is efficient, as no energy is wasted, and the overall efficiency remains high.

Advantages of Armature Voltage Control:

- ✓ **High Efficiency:** Since the motor operates in the constant torque region without any additional energy dissipation (such as in resistors), the overall efficiency remains high.
- ✓ **Precise Speed Control:** This method provides precise and smooth speed control over a wide range by adjusting the armature voltage.
- ✓ **Constant Torque:** The motor can maintain constant torque over the entire speed range, making it suitable for applications that require constant torque at varying speeds.
- ✓ **No Distortion in Characteristics:** The mechanical characteristics (torque-speed relationship) remain unchanged and shift parallel to each other when the voltage is varied, ensuring predictable and stable performance.

Disadvantages of Armature Voltage Control:

- **Limited Speed Range:** Speed can only be reduced below the nominal speed, and this method is not suitable for increasing the speed above the rated value.
- **Reduced Stability at Low Speeds:** At very low armature voltages, the system may become less stable, which can result in reduced control precision and possible overheating.
- **Voltage Supply Limitation:** The control is dependent on the available armature voltage, so if the voltage supply is limited, it may not be possible to achieve the desired speed range.
- **Not Suitable for All Applications:** For applications requiring variable torque or operation above the nominal speed, this method may not be effective, and other control strategies like flux control may be needed.

III.3.2 Flux Control (Field Weakening Control):

Once the motor reaches its nominal speed, the speed can be further increased by reducing the field flux. This is because the speed is inversely proportional to the excitation flux. This operation is known as ***under-excitation operation***.

In this speed range, the armature voltage U_a remains constant, but the motor cannot provide the nominal torque because the flux is gradually reduced. However, the power that the motor can deliver, without exceeding the nominal current, remains constant. This mode is referred to as ***constant power operation*** and typically only applies to around 5% of electric drive applications.

III.3.2.1 Mechanical Characteristic for Flux Control:($U_a = U_{an}$)

The governing relations are:

$$\begin{cases} \Omega = \frac{U_a - R_a I_a}{k \cdot \phi} \\ T_{em} = k \cdot \phi \cdot I_a \end{cases} \quad \text{(III. 16)}$$

- For $C_{em} = 0, I_a = 0 \Rightarrow \Omega = \frac{U_a}{k \cdot \phi}$. As the flux Φ decreases, the speed increases.
- For $\Omega = 0$ ona $I_a = \frac{U_a}{R_a} \Rightarrow T_{em} = k \cdot \phi \cdot \frac{U_a}{R_a}$. As the flux Φ decreases, the torque also decreases..

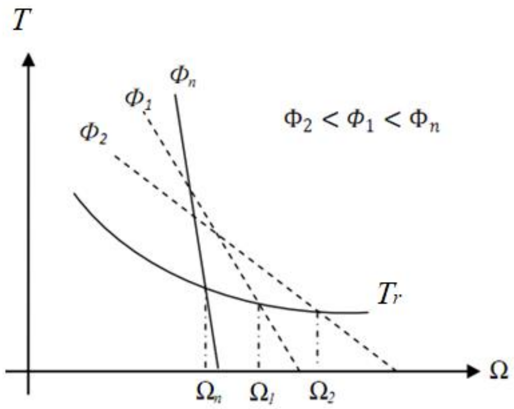


Figure. III. 6: The mechanical characteristic for flux control.

Analysis:

- **Technical Drawbacks:**
  - This method is technically unfavorable since the characteristics converge, making control less predictable and reliable.
- **Economic:**
  - Economically, it is efficient because the power dissipated in the field winding is very small compared to the power consumed by the motor, meaning the motor's efficiency remains unaffected.

Important Notes:

- The flux ϕ cannot be increased beyond its nominal value ϕ_n due to magnetic saturation limits.
- Reducing the flux increases the speed, but there is a potential issue with *over-speeding* or *demagnetization*.

Advantages of Flux Control (Field Weakening):

1. **Extended Speed Range:** This method allows the motor to operate at speeds higher than the nominal speed, which is useful in applications that require higher speeds beyond the base speed.
2. **Constant Power Operation:** The motor operates in a constant power mode during flux weakening, maintaining a steady power output despite the increase in speed, which can be advantageous for certain types of loads.
3. **Economically Efficient:** Since the power dissipated in the field winding is very low compared to the total motor power, the efficiency of the motor is not significantly impacted, making it an economically favorable method.
4. **Simplicity:** Flux control is relatively simple to implement by adjusting the excitation current.

Disadvantages of Flux Control (Field Weakening):

1. **Reduced Torque:** As the flux is reduced, the motor's torque capacity decreases. This means the motor cannot deliver nominal torque at high speeds, which may limit its usefulness in torque-demanding applications.
2. **Limited Speed Control Range:** Although the speed increases, this method only allows for a limited range of speed control and can lead to instability or reduced performance if overused.
3. **Risk of Demagnetization:** Excessive flux weakening can result in demagnetization of the motor's magnetic components, especially in cases where the flux is reduced too much, leading to motor damage or failure.
4. **Saturation Limitation:** The motor’s flux cannot be increased beyond a certain level (saturation limit), meaning this method only works for decreasing the flux and not increasing it beyond the nominal value.
5. **Converging Characteristics:** The mechanical characteristics tend to converge during flux weakening, making the control less stable and predictable compared to other methods like armature voltage control.

III.3.3 Armature Control Method (Rheostatic Control)

In this method, with the voltage and flux set to their nominal values, the resistance of the armature can be increased by adding a rheostat (Rh) in series. This control is used to reduce the speed from its nominal value. However, it has an undesirable effect due to energy dissipation.

III.3.3.1 Mechanical Characteristic of Rheostatic Control:

The governing relationships are:

$$\begin{cases} T_{em} = \grave{K} \cdot I_a \\ \Omega = \frac{U_a - (R_a + R_h) I_a}{\grave{K}} \end{cases} \quad \text{(III. 17)}$$

- For $T_{em} = 0$; $I_a = 0 \Rightarrow \Omega = \frac{U_a}{\grave{K}}$. This speed is independent of Rh, so the corresponding point is fixed.
- for $\Omega = 0$; $I_a = \frac{U_a}{R_a + R_h} \Rightarrow C_{em} = \grave{K} \frac{U_a}{R_a + R_h}$ As Rh increases, the torque decreases. This results in a set of converging straight lines, as shown in Figure III.7**.**
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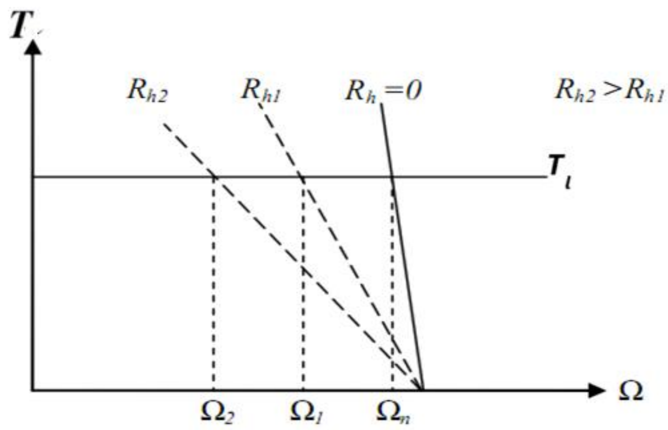


Figure. III. 7: The mechanical characteristic for Armature Control Method.

Analysis of Rheostatic Control:

- **Technical Disadvantages:** This method is technically inefficient. The mechanical characteristics converge as more resistance is added, making the speed drop more sharply with load. A technically sound control system should result in the characteristics shifting parallel to the original one, rather than converging.
- **Economic Disadvantages:** Economically, this method is also inefficient. The energy consumption in the rheostat increases significantly as the required speed reduction increases. At half speed, as much energy is wasted in the rheostat as is used by the motor. Therefore, this method is highly energy-inefficient.

Advantages:

1. **Simple Implementation:** Rheostatic control is simple and easy to implement without requiring advanced electronics or controllers.
2. **Effective for Starting and Braking:** This method is commonly used for starting the motor smoothly and for braking due to the ability to control speed temporarily.

Disadvantages:

1. **High Energy Losses:** Significant energy is dissipated in the form of heat in the rheostat, leading to poor efficiency, especially at lower speeds.
2. **Converging Characteristics:** The mechanical characteristics converge, meaning the speed decreases sharply with increasing load, resulting in unstable operation.
3. **Limited Control Range:** The speed can only be reduced from its nominal value, and the range of speed control is limited.
4. **Not Suitable for Continuous Operation:** Due to its inefficiency, this method is not suitable for continuous speed regulation and is typically reserved for starting or temporary braking.

III.4 Different Converters Used for Speed Control of DC Motors::

Speed variation in DC motors is typically achieved by adjusting the armature voltage and, optionally, the excitation voltage. Thus, the control requires a source of adjustable DC voltage. To obtain a variable DC voltage, there are two main methods:

1. **Starting from a Sinusoidal AC Voltage:**
   - Use a rectifier to convert the AC voltage into DC voltage.
2. **Starting from a Fixed DC Voltage:**
   - Use a chopper (DC-DC converter) to adjust the voltage.

Choosing the Converter:

The selection of the converter and its setup depends on several considerations:

- **Reversibility:** The ability to quickly reverse the direction of rotation. The converter must support operation in all four quadrants (Figure III.8).
- **Source:** The type of voltage source available (AC or fixed DC).
- **Power Requirements:** The power that needs to be delivered by the converter.
- **Electromagnetic Interference:** Minimizing electromagnetic disturbances.
- **Economic Criteria:** Cost-effectiveness of the converter and its setup.

Quadrants of Operation:

For reversible drives, the system must be able to operate in all four quadrants:

- **Quadrant 1:** Motor operation in the forward direction.
- **Quadrant 2:** Regenerative braking (acting as a generator) in the forward direction.
- **Quadrant 3:** Motor operation in the reverse direction.
- **Quadrant 4:** Regenerative braking (acting as a generator) in the reverse direction.

Figure III.8 illustrates these four quadrants, showing the various modes of operation for the motor and the converter.

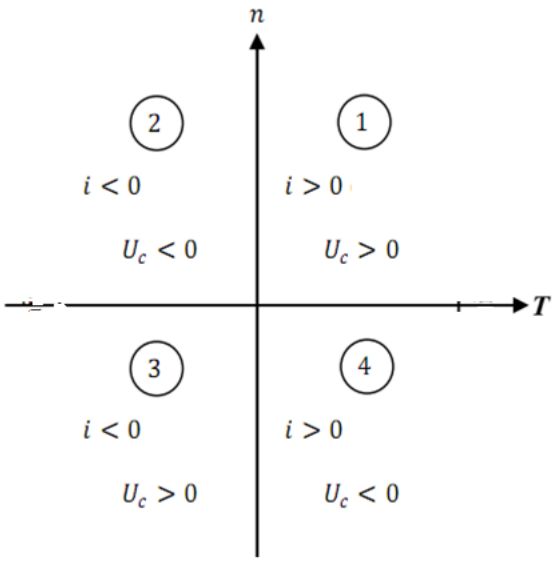


Figure. III. 8: The various modes of operation for the DC motor

III.4.1 Converters with Rectifiers:

Converters with rectifiers are widely used in industrial applications as they directly utilize the mains voltage (with or without a transformer). They can be single-phase or three-phase, depending on the motor's power requirements.

III.4.1.1 Single-Phase Rectifiers

n a single-phase rectifier setup, the armature circuit of the DC motor is connected to the output of the single-phase rectifier. The armature voltage can be varied by adjusting the firing angle α_a.

- **Firing Angle** α_a:
  - At a small firing angle, the armature current may become discontinuous, which increases losses in the motor. To mitigate this issue, a smoothing inductor L_m is connected in series with the armature to minimize the ripple to an acceptable level.
- **Field Control:**
  - The rectifier can also be used in the field circuit to control the excitation current by varying the firing angle α_{ex}.

Figure III.9 illustrates the single-phase rectifiers used to control DC motors.

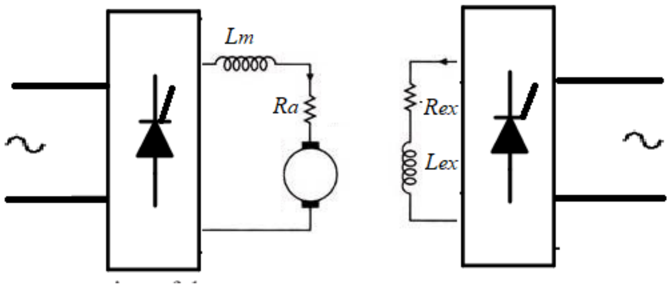


Figure. III. 9: The single-phase rectifiers used to control DC motors

Advantages of Single-Phase Rectifiers:

1. **Simplicity:** Single-phase rectifiers are straightforward to implement and cost-effective for smaller power applications.
2. **Widely Available:** They are commonly used in various industrial and commercial applications.

Disadvantages of Single-Phase Rectifiers:

1. **Ripple:** Single-phase rectifiers can introduce significant ripple in the DC output, which may require additional filtering components, such as smoothing inductors or capacitors.
2. **Limited Power Handling:** They are typically used for lower power applications. For higher power requirements, three-phase rectifiers are more suitable.
3. **Current Discontinuity:** At low firing angles, the armature current may become discontinuous, leading to increased losses and potentially reduced motor performance.

A)- Single-Phase Half-Wave Rectifiers:

Single-phase half-wave rectifiers are used to power the armature of a DC motor. In this setup, the armature current I_a is always discontinuous, which necessitates the use of a very large inductance in the armature circuit to smooth out the current.

- **Freewheeling Diode:**
    - A freewheeling diode is connected in parallel with the motor. This allows the motor to operate in the quadrant **q1** (forward motoring).

- **Power Limitation:**
  - This method is generally limited to applications with power requirements up to 0.5 kW.

Figure III.10 illustrates a single-phase half-wave rectifier used to control a separately excited DC motor.

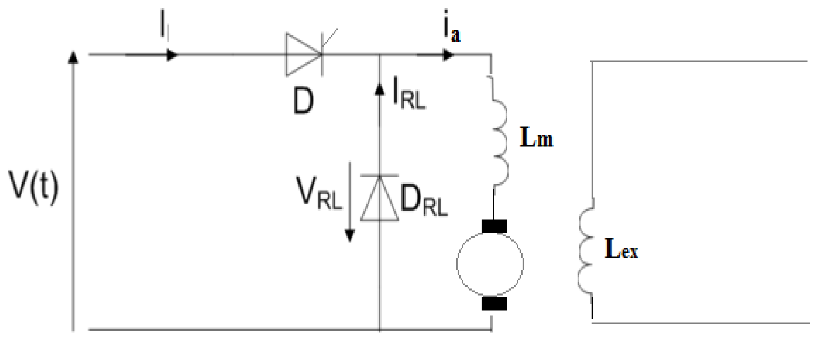


Figure. III. 10: a single-phase half-wave rectifier used to control a separately excited DC motor.

Characteristics of Single-Phase Half-Wave Rectifiers:

- **Output Voltage:**
  - The armature voltage V_a provided by a single-phase half-wave rectifier is given by:

$$V_a = \frac{V_m}{2\pi}(1 + \cos\alpha_a) \text{ for } \quad 0 < \alpha_a < \pi \qquad \textit{(III. 18)}$$

  - Here, V_m is the maximum AC voltage.

Advantages:

1. **Simple Design:** The half-wave rectifier is simple and cost-effective for low-power applications.
2. **Ease of Implementation:** It is straightforward to implement and use, making it suitable for small-scale applications.

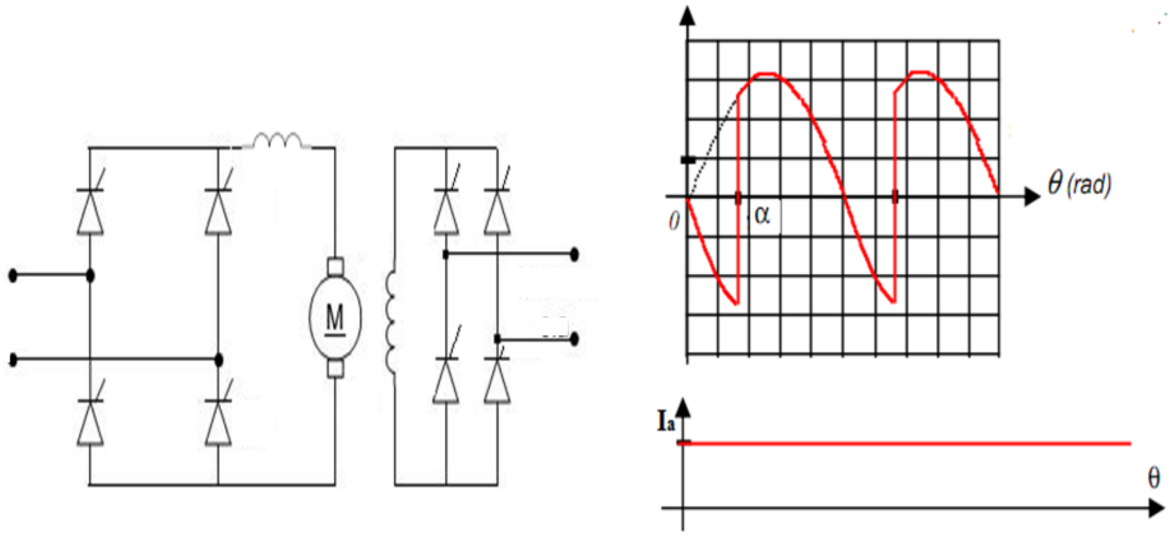
Disadvantages:

1. **Discontinuous Current:** The armature current is always discontinuous, which can lead to increased losses and reduced performance. A large inductance is required to smooth out the current.
2. **Increased Magnetic Losses:** Using a half-wave rectifier in the field circuit increases magnetic losses due to the high ripple current in the excitation circuit.
3. **Limited Power Capacity:** The power handling capability is limited to around 0.5 kW, restricting its use to low-power applications.

4. **Ripple and Efficiency Issues:** The high ripple in the output current can lead to inefficiencies and potential heating issues in the motor.

B)- Single-Phase PD2 Rectifiers

Single-phase PD2 rectifiers are used to power separately excited DC motors, as shown in **Figure III.11(a)**. Both the armature and the field circuits are supplied by a single-phase AC source through a PD2 rectifier.



a) Circuit diagram b) the voltage and current waveforms

Figure. III. 11: A single phase rectifier PD2 controlled the DC motor.

- **Armature Voltage (**V_a**)** and **Field Voltage (**V_{ex}**):**

The armature voltage is given by:

$$V_a = \frac{2V_m}{\pi}\cos\alpha_a \qquad \text{for} \quad 0 < \alpha_a < \pi \qquad \textit{(III. 19)}$$

The excitation voltage is similarly given by:

$$V_{ex} = \frac{2V_m}{\pi}\cos\alpha_{ex} \qquad \text{for} \quad 0 < \alpha_{ex} < \pi \qquad \textit{(III. 20)}$$

Here, V_m is the peak AC voltage, and α_a_aαa and α_{ex} are the firing angles for the armature and field circuits, respectively.

Operating Modes:

- $\boldsymbol{\alpha}$**< 90° :** Motor mode operation. The motor runs in forward motoring mode.
- $\boldsymbol{\alpha}$**=90°** : The motor is stopped but can still provide torque to hold a load (holding torque).
- $\boldsymbol{\alpha}$**> 90°** : Generator mode operation. The motor acts as a generator, feeding power back to the source.

In this configuration, the PD2 rectifier allows the machine to operate in two quadrants—**Quadrant 1** (forward motoring) and **Quadrant 4** (reverse regenerative braking), as shown in **Figure III.11(b)**, representing the voltage and current waveforms.

Advantages:

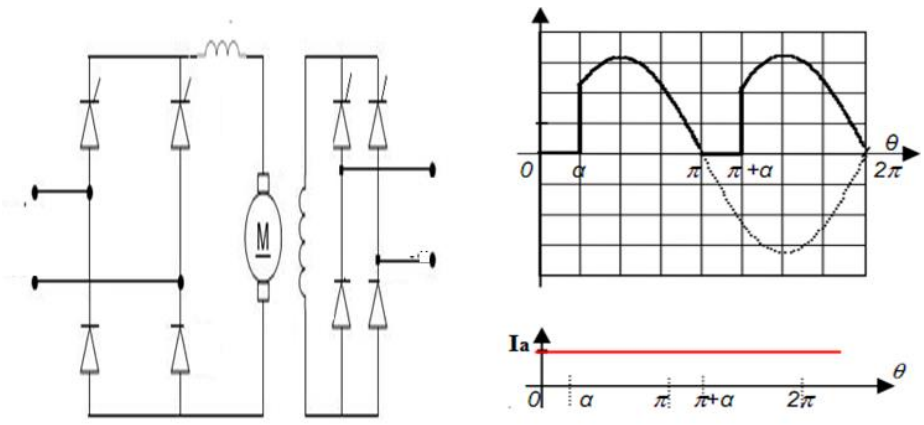
1. **Two-Quadrant Operation:** The PD2 rectifier allows for two-quadrant operation, enabling both forward motoring and regenerative braking in reverse.
2. **Simple Control Over Speed:** By adjusting the firing angle αa\alpha_aαa, the speed of the motor can be controlled smoothly.
3. **Regenerative Braking:** Operation in Quadrant 4 allows for regenerative braking, improving efficiency by feeding energy back to the supply.
4. **Flexibility:** The PD2 rectifier can easily switch between motor and generator modes, providing versatile operation for different applications.

Disadvantages:

1. **Current Ripple:** Similar to other rectifiers, the output current can contain ripples, requiring additional filtering to prevent inefficiency or overheating.
2. **Limited Quadrants:** The PD2 rectifier only supports operation in two quadrants, limiting its ability to handle more complex motor control applications, such as four-quadrant drives.
3. **Efficiency Concerns at Low Firing Angles:** At lower firing angles, the motor may experience discontinuous current, leading to increased losses and reduced performance.
4. **Complexity of Regenerative Braking:** Although regenerative braking is possible, it requires careful control and may introduce additional complexity in certain applications.

C)- Single-Phase Mixed PD2 Rectifiers:

A single-phase mixed PD2 rectifier is used for controlling a separately excited DC motor, as illustrated in Figure III.12 (a). The waveforms for the armature voltage Va and current Ia are shown in Figure III.12 (b).



a) Circuit diagram b) the voltage and current waveforms

Figure. III. 12: Single-Phase Mixed PD2 Rectifiers controlled the DC motor.

Characteristics:

- The motor is operated in **Quadrant 1** (forward motoring) with this setup.
- The **mixed PD2 rectifier** can supply DC motors for applications up to 15 kW. However, the converter used in the excitation circuit must also be of the mixed PD2 type.

Formulas:

- The armature voltage Va is given by:

$$V_a = \frac{V_m}{\pi}(1 + \cos\alpha_a) \quad \text{for} \quad 0 < \alpha_a < \pi \qquad (III.\ 21)$$

- The excitation voltage Vex is similarly given by:

$$V_{ex} = \frac{V_m}{\pi}(1 + \cos\alpha_{ex}) \quad \text{for} \quad 0 < \alpha_{ex} < \pi \qquad (III.\ 22)$$

Advantages:

1. **Higher Power Capacity:** The mixed PD2 rectifier can handle higher power, making it suitable for applications up to 15 kW, unlike the single-phase half-wave rectifiers.
2. **Improved Control:** Provides smoother control over the motor's operation and better regulation of the speed by controlling both the armature and field voltages.
3. **Reduced Ripple:** Compared to simpler rectifier types, this configuration offers less ripple in the output voltage and current, improving motor efficiency and reducing losses.
4. **Efficient Quadrant 1 Operation:** The motor operates efficiently in forward motoring (Quadrant 1), which is useful in many industrial applications.

Disadvantages:

1. **Limited to Quadrant 1:** This configuration is limited to operation in Quadrant 1, meaning it cannot support reverse or regenerative braking operations.
2. **Complexity:** The design is more complex than basic half-wave or full-wave rectifiers, requiring more components and control for proper operation.
3. **Power Limitation:** Even though it supports higher power than simpler rectifiers, the power capacity is still limited to around 15 kW, which may not be sufficient for higher-power applications.
4. **Dependence on Mixed Excitation:** The excitation circuit must also be controlled by a mixed PD2 converter, adding to the complexity and cost.

D)- Dual Converters

In applications where the motor needs to operate in **both directions** with quick transitions between them, electrical braking must be applied by feeding energy back to the network (i.e., switching from **Quadrant 1 to Quadrant 2** or from **Quadrant 3 to Quadrant 4**). Since a fully thyristor-based rectifier is only reversible in voltage, achieving the necessary **current reversibility** requires a more advanced solution.

"Back-to-Back" Setup Explanation:

The most efficient method is to connect two fully thyristor-controlled rectifiers in **antiparallel** across the armature terminals of the motor. This means that two **PD2 converters** are connected in **opposite directions** across the motor:

- **Rectifier 1** provides **positive current**.
- **Rectifier 2** provides **negative current**.

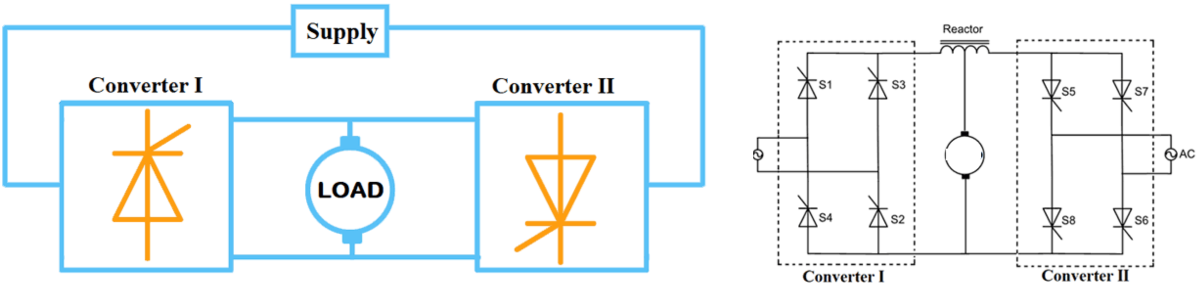


Figure. III. 13 : dual converters for variable speed DC drives.

Four-Quadrant Operation:

- **converter 1** operates the motor in **Quadrants 1 and 4** (forward motoring and reverse braking).
- **converter 2** operates the motor in **Quadrants 2 and 3** (reverse motoring and forward braking).

This arrangement allows the motor to operate in all **four quadrants**, providing smooth transitions between motoring and braking modes in both directions. The setup is commonly used in applications requiring fast reversals, such as industrial machinery.

Power Limitation:

- The back-to-back converter configuration is limited to applications up to **15 kW**.

Generator Mode and Reversing Power Flow:

- In **generator mode**, to reverse the power flow direction, the electromotive force (EMF) of the motor can be reversed by adjusting the **excitation flux**.
- The excitation circuit should also use a **PD2 converter** for controlled flux reversal.

Operation of Converters:

Converter 1 operates with firing angle α_{a1} , providing the armature voltag

$$V_a = \frac{2V_m}{\pi}\cos\alpha_{a1} \quad \text{for } 0 < \alpha_{a1} < \pi \qquad (III.\ 23)$$

Converter 2 operates with firing angle α_{a2} , providing the armature voltage:

$$V_a = \frac{2V_m}{\pi}\cos\alpha_{a2} \text{ for } 0 < \alpha_{a2} < \pi \tag{III. 24}$$

Where $\alpha_{a2} = \pi - \alpha_{a1}$, ensuring proper switching between the two converters.

Advantages:

1. **Four-Quadrant Operation:** The motor can operate smoothly in both directions with braking and regeneration, allowing for fast, efficient transitions.
2. **Fast Reversals:** The setup allows for **rapid reversals** of the motor's direction, which is crucial for applications that require frequent direction changes.
3. **Efficient Power Regeneration:** During braking, the energy can be fed back to the power grid, increasing overall system efficiency.

Disadvantages:

1. **Complexity:** The system is more complex, requiring **two thyristor bridges** and additional control circuitry, which increases installation and maintenance costs.
2. **Limited Power:** The configuration is typically limited to applications up to **15 kW**, which may not be sufficient for larger industrial motors.
3. **Increased Size and Cost:** The dual converter arrangement increases the overall **size and cost** of the motor drive system.

This method is commonly used in applications like cranes, elevators, and other systems where quick direction changes and precise control are required.

III.4.1.2 Three-Phase Rectifiers for DC Motor Control

The armature of the DC motor is connected to the output of a controlled three-phase converter. Three-phase rectifiers are used in high-power applications, typically reaching megawatt (MW) levels. Compared to single-phase rectifiers like the PD2, three-phase rectifiers offer several advantages in performance and efficiency.

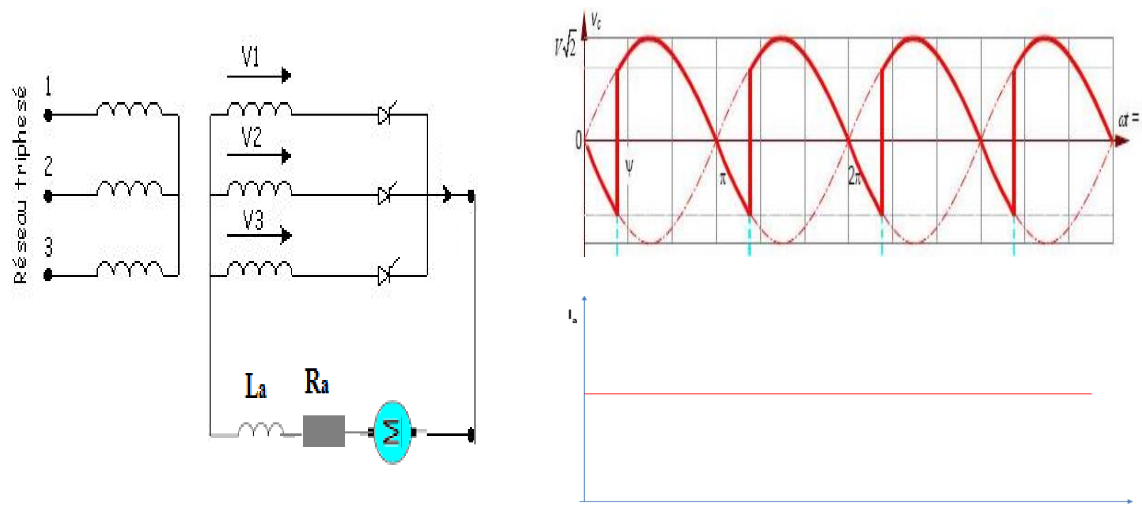
Advantages of Three-Phase Rectifiers:

1. **Higher Power Capability:**
   - Three-phase rectifiers are suited for applications requiring high power, up to several megawatts.
2. **Reduced Ripple:**
   - The voltage ripple frequency Va is higher compared to PD2, allowing for smoother output. This means a smaller inductance is required in the armature circuit, improving motor performance.

3. **Continuous Armature Current:**
   - The armature current is more continuous, leading to better motor performance with fewer interruptions in torque output compared to PD2-based drives.

A)- Simple Three-Phase Bridge (P3)

The control block of a DC motor driven by a three-phase bridge rectifier P3 is illustrated in Figure III.14 (a).



a) Circuit Diagram b) the waveform of the armature voltage and current.

Figure. III. 14: A simple three-phase bridge rectifier (P3) controlling a DC motor.

The armature voltage Va for the three-phase rectifier P3 is given by:

$$V_a = \frac{3\sqrt{3}V_m}{2\pi}\cos\alpha_a \quad \text{for} \quad 0 < \alpha_a < \pi \qquad \textit{(III. 25)}$$

Operation and Applications:

- The P3 three-phase bridge rectifier enables the motor to operate in **two quadrants**
- This configuration is suitable for applications up to **40 kW**.
- The excitation circuit can be supplied by either a single-phase or three-phase converter, depending on the application.

Advantages of the P3 Bridge:

1. **High Power Handling:** The P3 bridge is used for medium to high-power applications, handling up to 40 kW.
2. **Smooth Output:** With a higher ripple frequency, the P3 bridge provides smoother DC output, improving motor performance and reducing the size of filtering inductors needed in the circuit.

3. **Better Efficiency:** Continuous armature current leads to improved efficiency compared to single-phase rectifiers like PD2.

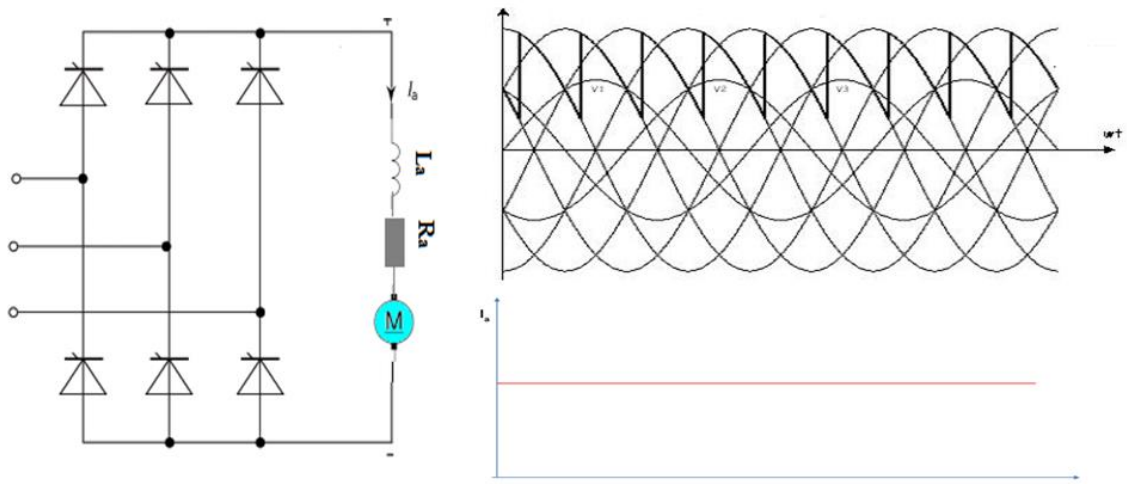
Limitations:

1. **Two-Quadrant Operation:** The simple P3 bridge can only operate in two quadrants, limiting its use in applications requiring four-quadrant operation.
2. **Complexity:** While more efficient than single-phase systems, three-phase converters require more complex control circuitry, increasing the cost and complexity of the system.

Overall, the three-phase P3 bridge is commonly used in industrial applications where high power and continuous motor performance are essential, such as in large-scale manufacturing, conveyor systems, and heavy-duty motor drives.

B)- Double Three-Phase Bridge Rectifier (PD3)

The PD3 rectifier is a double three-phase bridge rectifier commonly used to drive DC motors in industrial applications, especially those requiring high power. This configuration is effective for operating in two quadrants and can handle significant **power levels**



a) circuit diagram b) the waveform of the armature voltage and current

.***Figure. III. 15:*** double three-phase bridge rectifier (PD3) driving a DC motor..

The average armature voltage Va produced by the PD3 rectifier is given by the equation:

$$V_a = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha_a \quad \text{for} \quad 0 < \alpha_a < \pi \qquad \textit{(III. 26)}$$

Operation in Two Quadrants:

- The PD3 converter operates in **two quadrants**:
  - **Quadrant 1**: Motor running in the forward direction (motoring mode).

- **Quadrant 4**: Motor running in the reverse direction (regenerative braking mode).

This configuration allows for smooth control of the motor in forward and reverse directions, with the ability to recover energy during braking by feeding it back into the power grid.

Power Capabilities:

- The PD3 rectifier can be used for high-power applications up to **1500 kW**.

Generator Mode and Power Reversal:

- In generator mode, to reverse the direction of power, the back electromotive force (EMF) of the motor is reversed by changing the direction of the excitation. This requires the excitation circuit's converter to be reversible, allowing it to function in both forward and reverse modes.

Advantages of the PD3 Rectifier:

1. **High Power Handling:** Capable of handling large power loads up to **1500 kW**, making it suitable for heavy industrial applications.
2. **Two-Quadrant Operation:** The motor can operate in motoring and regenerative braking modes, providing flexibility for applications that require frequent speed control and braking.
3. **Efficient Energy Recovery:** During regenerative braking, the PD3 rectifier allows energy to be fed back into the grid, improving overall system efficiency and reducing energy waste.

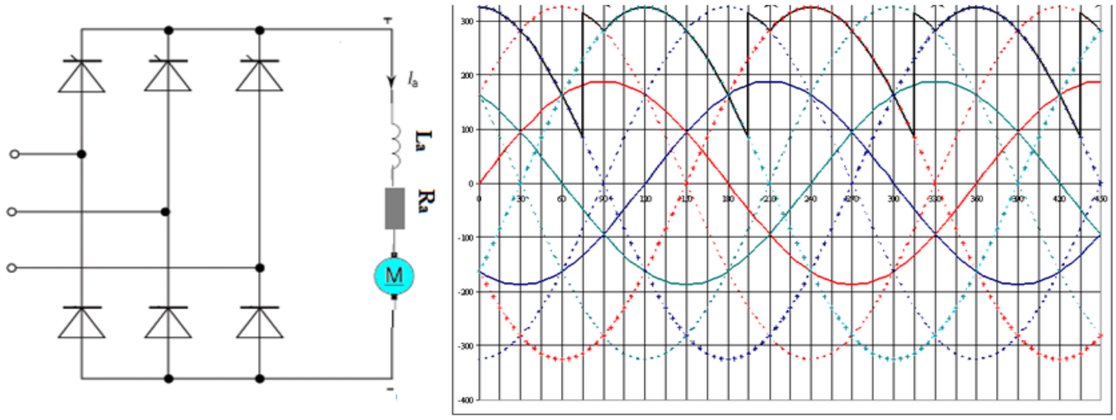
Limitations:

1. **Complexity and Cost:** The PD3 rectifier is more complex and expensive compared to single-phase or simpler three-phase converters.
2. **Two-Quadrant Limitation:** While effective for many applications, the PD3 rectifier is limited to two-quadrant operation, making it unsuitable for applications requiring four-quadrant operation (where both forward/reverse motoring and forward/reverse regeneration are needed).

The PD3 rectifier is commonly used in large industrial systems where high power and efficient energy management are essential, such as in large conveyor systems, cranes, and heavy-duty electric drives.

C)- Mixed Three-Phase Bridge :

The Mixed Three-Phase Bridge rectifier used to control the speed of separately excited DC motors. This setup is typically used for medium power applications where speed control in the forward direction (**quadrant 1**) is needed.



a) Circuit diagram b) The waveform of the armature voltage.

Figure. III. 16: a mixed three-phase bridge rectifier driving a DC motor.

The average armature voltage Va is given by the equation:

$$V_a = \frac{3\sqrt{3}V_m}{2\pi}(1 + \cos\alpha_a) \quad \text{for} \quad 0 < \alpha_a < \pi \qquad (III.\ 27)$$

Operation in Quadrant 1:

- The PM3 rectifier enables the motor to operate in **quadrant 1**, meaning it runs the motor in the forward motoring mode.

This configuration is suitable for applications where the motor runs in one direction and does not require regenerative braking or reverse operation.

For the separately excited DC motor, the excitation voltage Vex is also controlled by a PM3 rectifier, and the voltage is given by:

$$V_{ex} = \frac{3\sqrt{3}V_m}{2\pi}(1 + \cos\alpha_{ex}) \quad \text{Pour } 0 < \alpha_{ex} < \pi \qquad (III.\ 28)$$

Power and Application Limitations:

- The PM3 rectifier is typically limited to **applications up to 115 kW**.
- It is mainly used for systems where the motor runs in a single direction without needing advanced braking or multi-quadrant operation.

Advantages of the PM3 Rectifier:

1. **Simpler Circuit Design:** Compared to more complex four-quadrant converters, the PM3 rectifier offers a simpler design for controlling DC motors in forward operation.

2. **Medium Power Applications:** Suitable for applications requiring moderate power levels, up to **115 kW**, making it useful in many industrial scenarios.
3. **Stable Speed Control:** Provides effective speed control in quadrant 1, ensuring the motor runs smoothly in the forward direction.

Disadvantages:

1. **Single Quadrant Operation:** The PM3 rectifier can only operate in **quadrant 1**, which limits its ability to handle reverse motion or regenerative braking. This restricts its use in applications that require dynamic motor control.
2. **Limited Power Range:** While it is suitable for medium power applications, it cannot handle power levels beyond **115 kW**, making it unsuitable for very large industrial systems.

Overall, the PM3 rectifier is commonly used in moderate industrial applications where simple and reliable speed control in one direction is sufficient. Examples include conveyor systems and production lines.

D)- Three-Phase Dual Converter:

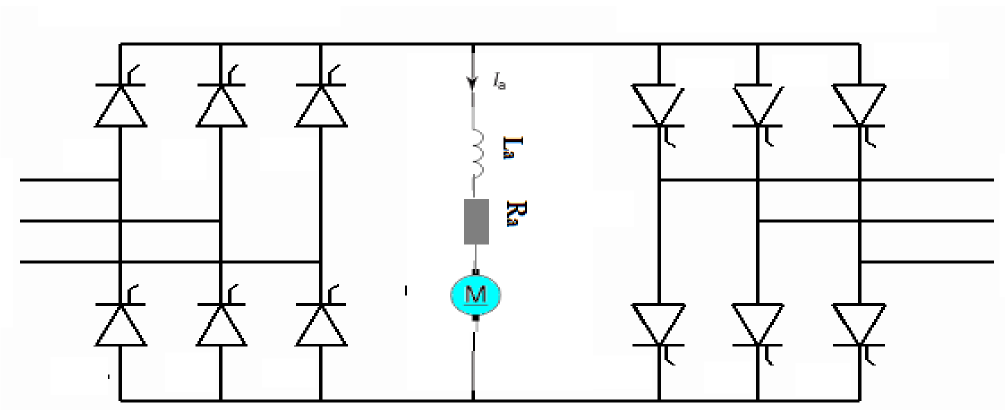


Figure. III. 17 : Three-Phase Dual Converter Driving a DC Motor

The Three-Phase Dual Converter is designed to allow **four-quadrant operation** of a DC motor. This means that both the armature voltage and current can be reversible, enabling the motor to operate in both directions and recover energy during braking.

Operating Principle:

In this setup, two PD3 rectifiers are connected in back-to-back across the armature terminals. Each rectifier can function as either a rectifier or an inverter, depending on the firing angle α. The first rectifier controls quadrants 1 and 4, while the second controls quadrants 2 and 3.

1. **Rectifier 1: Quadrants 1 and 4**
   - When α1<90∘, the **rectifier functions as a rectifier**, producing positive voltage and current, making the motor operate in the **first quadrant**. Power flows from the source to the motor.
   - When α1>90∘, the **rectifier functions as an inverter**, generating negative voltage while keeping the current positive. This places the motor in the **fourth quadrant**, allowing energy to be recovered and returned to the power source.
2. **Rectifier 2: Quadrants 2 and 3**
   - When α2<90∘, the **rectifier functions as a rectifier** but with negative voltage and current. The motor operates in the **third quadrant**, with the rotation direction reversed and power transferred from the load to the source.
   - When α2>90∘, the **rectifier functions as an inverter** with positive voltage but negative current, placing the system in the **second quadrant**, where power flows from the armature to the source.

The average armature voltages for the two rectifiers are given by:

- For **rectifier 1**:

$$V_a = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha_{a1} \quad \text{for} \quad 0 < \alpha_{a1} < \pi \qquad \textit{(III. 29)}$$

- For **rectifier 2**:

$$V_a = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha_{a2} \quad \text{for} \quad 0 < \alpha_{a2} < \pi \qquad \textit{(III. 30)}$$

Advantages of Three-Phase Dual Converter Driving a DC Motor:

1. **Bidirectional Control**: The dual converter allows bidirectional power flow, enabling the motor to run in both forward and reverse directions.
2. **Four-Quadrant Operation**: It enables four-quadrant operation (forward motoring, reverse motoring, forward braking, reverse braking), which is essential for applications requiring regenerative braking and precise speed control.
3. **Smooth Transition**: The converter can provide smooth and controlled transitions between different operational modes (motoring and braking) without significant mechanical or electrical disruptions.
4. **High Power Handling**: Using three-phase power provides the ability to drive higher power motors with better efficiency, especially in industrial applications requiring significant torque.

5. **Improved Efficiency**: Three-phase converters offer higher efficiency and smoother torque compared to single-phase systems, reducing harmonics and improving power quality.
6. **Controlled Speed and Torque**: Precise control of the motor's speed and torque is achievable through accurate control of the firing angles of the converter thyristors.

Disadvantages of Three-Phase Dual Converter Driving a DC Motor:

1. **Complexity**: The control circuitry required for a three-phase dual converter is more complex compared to single-phase converters, requiring more advanced control algorithms and additional components.
2. **High Cost**: Due to the complexity and additional components (e.g., thyristors, control units), the cost of a three-phase dual converter system is higher than simpler motor drive systems.
3. **Harmonics and Power Quality**: Although improved over single-phase systems, a three-phase converter still introduces harmonics into the power supply, which may affect other connected equipment and requires filtering.
4. **Heat Generation**: The high current involved in driving large DC motors leads to significant heat generation, requiring effective cooling systems, increasing maintenance and operational costs.
5. **Size and Space Requirements**: The physical size of three-phase dual converters, along with associated cooling systems, can be larger, requiring more installation space.
6. **Commutation Issues**: The converters may face commutation problems at low speeds, leading to inefficiency or operational challenges, particularly in applications requiring low-speed operation.

III.4.2 Chopper-based Drives

Chopper-based drives are a type of power electronic control system used to vary the speed and torque of DC motors by regulating the voltage applied to the motor's armature.

If the available network is a DC network, then the static converter associated with the DC motor can only be a chopper. This control is achievable either by acting on the armature voltage or by acting on the flux. This type of drive is commonly used in applications requiring efficient control of DC motors.

Given that the DC network comes from:

- Batteries, or
- A diode rectifier.

Comparison: Chopper-based Drives vs Converter Drives for DC Motors

When deciding between **chopper-based drives** and **converter drives** for controlling DC motors, several factors come into play, including application requirements, efficiency, cost, and control flexibility. Below is a detailed comparison to help you choose between them.

1. Power Supply Requirements:

- **Chopper-based Drive**:
  - Requires a **DC power source** (batteries or rectified AC). It cannot operate directly from AC networks without an external rectifier.
  - Common in systems where DC sources are available, such as electric vehicles or battery-powered applications.
- **Converter Drive**:
  - Works with **AC power supply**, converting it into the DC voltage needed to drive the motor.
  - More versatile when used in systems connected to the AC grid, eliminating the need for a separate rectifier.

2. Efficiency:

- **Chopper-based Drive**:
  - Generally more efficient because it uses high-frequency switching to control the motor's voltage with minimal energy loss.
  - Suitable for applications requiring energy-efficient operation, especially in **low to medium power** ranges.
- **Converter Drive**:
  - **Less efficient** than choppers due to power losses in the AC-DC conversion and the use of thyristors (SCRs), especially in lower-speed operations.
  - However, in **high-power applications**, converters can be more practical and stable.

3. Speed and Torque Control:

- **Chopper-based Drive**:
  - Offers **precise speed control** by varying the duty cycle of the voltage applied to the motor.
  - Ideal for applications requiring fine speed adjustments and dynamic control.
- **Converter Drive**:
  - Provides good control, but **less precise** than choppers at higher speeds, especially in basic thyristor-based converters.

   - Better for applications where **smooth torque** and **four-quadrant operation** (motoring, braking, forward, and reverse) are essential.

4. Harmonics and Noise:

- **Chopper-based Drive**:
   - High-frequency switching generates **harmonic distortion** and **electromagnetic interference (EMI)**. This may require additional filtering to avoid noise issues, especially in sensitive environments.
- **Converter Drive**:
   - **Lower harmonic distortion** compared to choppers, particularly when using phase-controlled rectifiers. Converters are generally quieter in terms of EMI.

5. Power Handling:

- **Chopper-based Drive**:
   - Suitable for **low to medium power** applications. It is less effective in **very high-power** applications because switching losses increase with higher current levels.
- **Converter Drive**:
   - Can handle **higher power loads** more efficiently, especially in three-phase AC systems. Suitable for **industrial and large-scale** motor applications.

6. Cost and Complexity:

- **Chopper-based Drive**:
   - Generally more **expensive** due to the advanced semiconductor devices (e.g., MOSFETs or IGBTs) and complex control circuits required for high-frequency switching.
   - **Complex control** algorithms are needed, especially for managing switching frequencies and minimizing ripple.
- **Converter Drive**:
   - **More cost-effective** for high-power applications, particularly when using thyristor-based converters, which are robust and simpler to control.
   - Suitable for applications that do not require frequent or fast switching.

7. Voltage Ripple and Torque Pulsations:

- **Chopper-based Drive**:
   - The **pulsed nature** of the voltage output can cause **ripple** in the motor current, leading to torque pulsations, especially at low speeds.

- **Converter Drive**:
    - Provides **smoother voltage** and current output, resulting in **more stable torque** with fewer fluctuations, particularly at low speeds.

Choosing Between Chopper-based and Converter Drives:

Use a Chopper-based Drive if:

- You have a **DC power source** available (like batteries).
- The application requires **precise speed control** and **dynamic response** (e.g., electric vehicles, robotics).
- **Energy efficiency** is a priority, especially in **low to medium power** applications.
- Compactness and **fast switching** are needed.

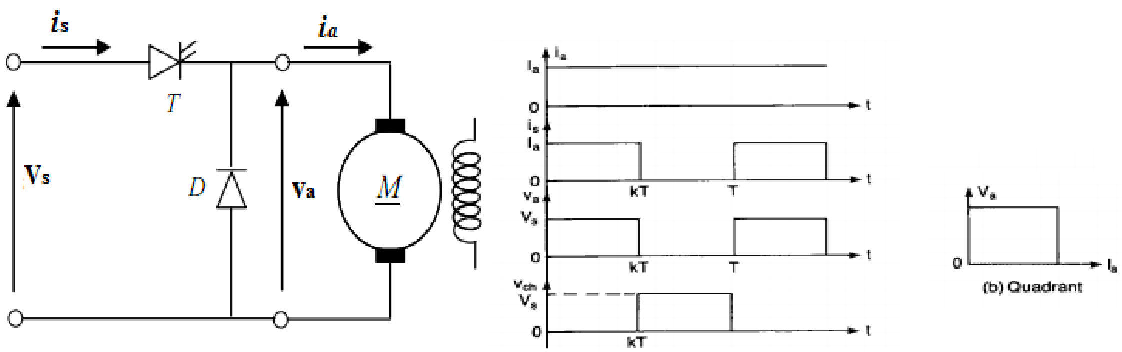
Use a Converter Drive if:

- You are working with an **AC power supply** and need to convert it to DC.
- You require **high-power handling**, such as in industrial motors or heavy-duty machinery.
- **Four-quadrant operation** (motoring and braking in both directions) is critical.
- You prefer a simpler and **more cost-effective** solution for high-power applications with moderate control requirements.

As a conclusion:

- For **low-power, DC-powered applications** with high precision, a **chopper-based drive** is better.
- For **high-power, AC-supplied applications** with less complex control needs, a **converter drive** would be more practical.

III.4.2.1 Buck Converter (Series Chopper)



a) Circuit Diagram b) Voltage and Current Waveforms

Figure. III. 18: Association of a Series Chopper with a DC Motor.

The chopper is used to control the armature voltage Va of the DC motor. This setup operates the machine in the **first quadrant (Q1)**. In general, series choppers are typically used in low to medium power applications ranging from around a few hundred watts to 20 kW

The armature voltage is:

$$V_a = k.V_s \quad (III.\ 31)$$

Where k is the **duty cycle**:

$$k = \frac{t_{on}}{T} \quad (III.\ 32)$$

The power supplied to the motor is :

$$P_a = V_a.I_a = k.V_s.I_a \quad (III.\ 33)$$

The equivalent input resistance of the chopper is:

$$R_{eq} = \frac{1}{k}\frac{V_s}{I_a} \quad (III.\ 34)$$

To vary the speed of the DC motor, it is sufficient to vary the duty cycle k

Advantages of Associating a Series Chopper with a DC Motor:

1. **Precise Speed Adjustment**:
   - By varying the duty cycle (k), precise control of the motor's speed is achieved, allowing for accurate adjustments based on the load and operational requirements.
2. **Simple Circuit Design**:
   - The circuit design of a series chopper is relatively simple, especially for low and medium power applications, reducing overall system complexity.
3. **Reduced Power Losses**:
   - Since the chopper operates using high-frequency switching, it minimizes power dissipation in the control elements, reducing thermal losses and improving overall system efficiency.
4. **Compact and Lightweight**:
   - Compared to other types of control systems, the use of power electronics makes the system more compact and lighter, ideal for space-constrained applications.
5. **Low Maintenance**:
   - Solid-state components used in chopper circuits (e.g., MOSFETs, IGBTs) have no moving parts, leading to lower maintenance requirements and longer operational life.

Disadvantages of Associating a Series Chopper with a DC Motor:

1. **Harmonic Distortion**:
   - The pulsed output from the chopper can introduce harmonics into the motor's current, leading to distorted waveforms that might affect performance and create unwanted vibrations or noise.
2. **Torque Ripple**:
   - The intermittent nature of the current delivered to the motor can cause ripple in the motor’s torque output, leading to vibrations and potentially uneven mechanical performance at lower speeds.
3. **Limited Power Handling**:
   - Series choppers are typically suited for **low to medium power** applications. In very high-power applications, the switching elements (MOSFETs, IGBTs) may not be as efficient, and switching losses become more significant.
4. **Component Stress**:
   - The rapid switching in chopper circuits can lead to electrical and thermal stress on the components, reducing their lifespan or necessitating the use of more robust (and often more expensive) components.
5. **Design Complexity at High Power**:
   - In high-power applications, the design becomes more complex due to the need for larger and more efficient switching devices, better thermal management, and more advanced control algorithms.

III.4.2.2 Reversible Current Chopper for DC Motors

In a reversible current chopper, also called a two-quadrant chopper, the DC motor can operate in both the first and second quadrants of the torque-speed plane. This type of chopper allows for bidirectional control of the motor's current and torque, making it ideal for applications where both motoring and regenerative braking are required.

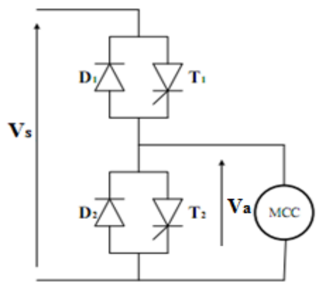
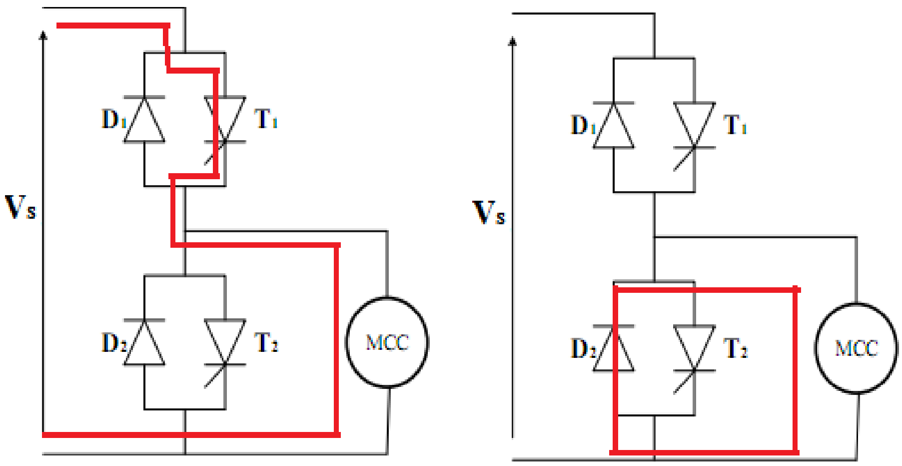


Figure. III. 19: Association hacheur réversible en courant-MCC

Operating Modes:

1. Power Control Mode (Motoring Mode)

- **Components**: Thyristor T1 and Freewheeling Diode D2
- **Operation**:
  - **Thyristor T1**: When T1 is triggered (conducting), it connects the DC voltage source Vs to the motor terminals, causing the motor to run forward (figure.III.20. a).
  - **Diode D2**: When T1 is off, the inductive current in the motor's armature flows through D2. This keeps the current flowing and prevents the sudden interruption that could cause electrical arcing or mechanical issues (figure.III.20 b).
- **Waveforms**:
  - **Voltage**: Positive Va.
  - **Current**: Positive Ia.
- **Quadrant**: Operates in **Quadrant 1**, where both voltage and current are positive, resulting in forward motoring.
-



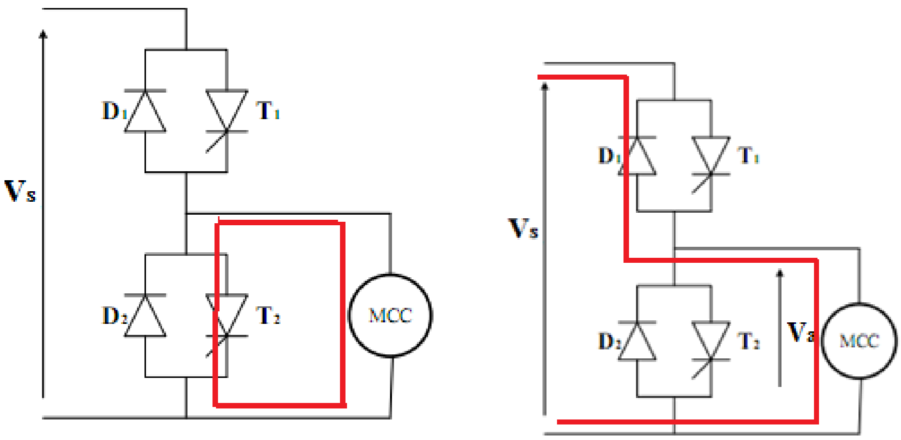
A b

Figure. III. 20: Power Control Mode

Generation Control Mode (Regenerative Braking Mode)

- **Components**: Thyristor T2 and Diode D1
- **Operation**:
  - **Thyristor T2**: When T2 is triggered (conducting), it effectively short-circuits the motor's terminals, allowing the motor to operate as a generator (figure.III.21.a).

  - **Diode D1**: When T2 is off, the generated energy is transferred back to the supply through D1, enabling regenerative braking. (figure.III.21. b).
- **Waveforms**:
  - **Voltage**: Zero or near zero Va.
  - **Current**: Negative Ia (current flows back to the supply).
- **Quadrant**: Operates in **Quadrant 2**, where the current is negative and the motor is braking or generating energy.



a b

Figure. III. 21: Generation Control Mode.

The voltage and current waveforms for a reversible current chopper exhibit alternating pulses depending on which thyristor is conducting. During motoring, the voltage is positive, and during regenerative braking, the current can reverse direction, causing energy to flow back into the source (Figure III.22).

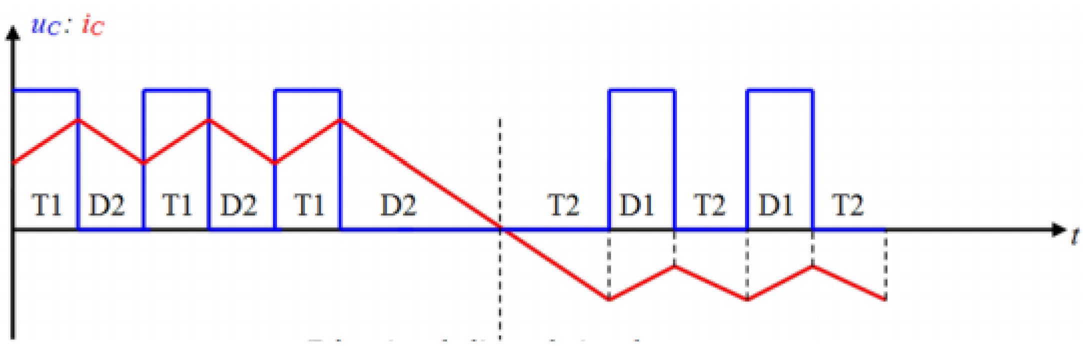


Figure. III. 22: The voltage and current waveforms for a reversible current chopper**.**

A reversible current chopper is typically used for medium to high power DC motor control applications, depending on the type of thyristors or transistors used in the circuit. The power range for such applications generally falls within: 1 kW to 100 kW

Advantages:

1. **Energy Recovery**:
   - **Regenerative Braking**: This feature allows the motor to return energy to the power supply during braking, improving overall system efficiency and reducing energy costs. This is particularly beneficial in applications with frequent braking and acceleration cycles, such as elevators and electric vehicles.
2. **Bidirectional Operation**:
   - The reversible current chopper allows for both forward and reverse operation of the motor. This flexibility is crucial for applications requiring bidirectional control, such as robotics, conveyor systems, and material handling equipment.
3. **Improved Control**:
   - **Smooth Transitions**: The chopper provides smooth transitions between motoring and braking modes, reducing mechanical stress and wear on the motor and associated components.
   - **Precise Speed and Torque Control**: By controlling the armature voltage and current, the chopper offers precise control over the motor's speed and torque, improving overall performance and adaptability to varying load conditions.

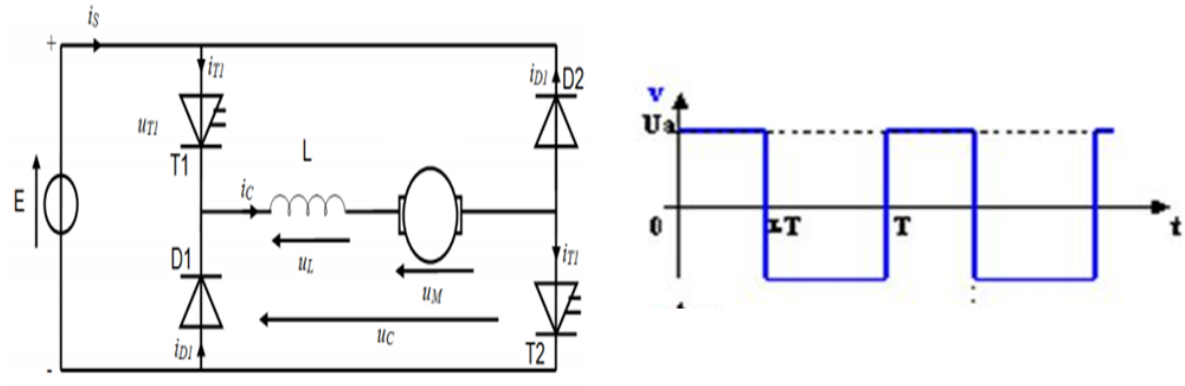
Disadvantages:

1. **Complexity of Control**:
   - **Timing and Synchronization**: Proper control of the thyristors and diodes requires precise timing and synchronization to ensure smooth operation and avoid issues like electrical arcing or inefficient braking.
   - **Control Circuit Complexity**: The control circuits for managing the switching of thyristors and handling regenerative braking can be complex, requiring advanced control strategies and feedback mechanisms.
2. **Harmonic Distortion**:
   - The switching nature of the chopper can introduce harmonics into the motor's current and voltage waveforms, potentially causing torque ripple and mechanical vibrations.
3. **Component Stress**:
   - **Stress on Thyristors**: The rapid switching and high current handling can stress the thyristors and diodes, potentially reducing their lifespan and requiring robust, high-quality components.

4. **Efficiency Considerations**:
   - While the chopper is efficient in regenerative braking, the efficiency of the overall system can be affected by switching losses and the need for additional components for filtering and cooling.

III.4.2.3 Reversible Voltage Chopper for DC Motors:

A **reversible voltage chopper** (also called a **two-quadrant chopper**) is used to control the **output voltage** applied to a DC motor, (La figure.III.23.a) allowing the motor to operate in two quadrants: forward motoring and forward regenerative braking. This means the motor can operate with a positive current, but the applied voltage can be both positive (for motoring) and negative (for braking).



a) Digramme de circuit B) La forme d'onde de tension

Figure. III. 23: Association hacheur réversible en tension -MCC

Circuit Operation:

In a **two-quadrant reversible voltage chopper**, the voltage across the motor's armature can switch between positive and negative values (figure.III.23.b), but the current always flows in one direction. This allows for both motoring and regenerative braking, but only in the **forward direction**.

The key components in the circuit are two controlled switches (e.g., thyristors or transistors) and two diodes, which manage the flow of current and the reversal of the applied voltage.

Control Phases:

1. **Motoring Mode (Positive Voltage)**:
   - In this mode, the switches (T1 and T2) are closed, applying the **positive voltage** +E across the motor.
   - The motor accelerates, and the current flows in the positive direction.

- During this phase, the motor operates in **Quadrant 1** (positive voltage and positive current).

2. **Regenerative Braking Mode (Negative Voltage)**:
   - When T1 and T2 are turned off, the current continues to flow through the freewheeling diodes (D1 and D2). The applied voltage is now negative −E, causing the motor to decelerate.
   - The motor acts as a generator, converting mechanical energy into electrical energy, which is returned to the power source.
   - In this phase, the motor operates in **Quadrant 2** (negative voltage, positive current).

Average Output Voltage:

The average output voltage Va can be controlled by adjusting the duty cycle α of the switches:

$$V_a = (2\alpha - 1).V_s \Rightarrow \begin{cases} V_a > 0 \ldots\ldots \text{si} \ldots\ldots\ldots \alpha > \frac{1}{2} \\ V_a < 0 \ldots\ldots \text{si} \ldots\ldots\ldots \alpha < \frac{1}{2} \end{cases} \qquad (III.\ 35)$$

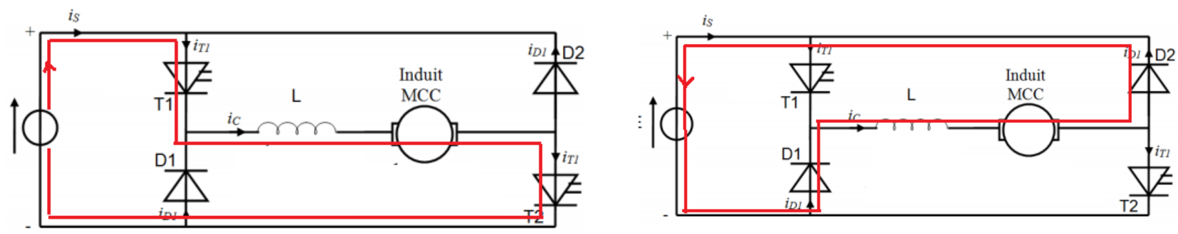


Figure. III. 24: Fonctionnement circuit hacheur réversible en tension

Advantages:

1. **Two-Quadrant Operation**: Allows the motor to operate in **forward motoring** and **regenerative braking** modes, making it ideal for applications requiring deceleration and energy recovery.
2. **Regenerative Braking**: Enables energy recovery during braking, feeding it back to the power source, improving efficiency.
3. **Simple Design**: The circuit is simpler compared to four-quadrant choppers, as it only controls voltage reversal without reversing the current.

Disadvantages:

1. **Unidirectional Current**: Since the current cannot be reversed, the chopper cannot operate the motor in reverse (Quadrants 3 and 4 are not accessible).

2. **Limited Applications**: It's suitable only for systems requiring forward motoring and regenerative braking, but not reverse motoring.

III.4.2.4 Bridge Chopper

A **bridge chopper** is used for controlling DC motors when operation in **four quadrants** is required. This means the motor can function in both motoring and generating modes, in both forward and reverse directions. This type of chopper is particularly useful in applications where bidirectional control of both voltage and current is necessary(figure III.25).

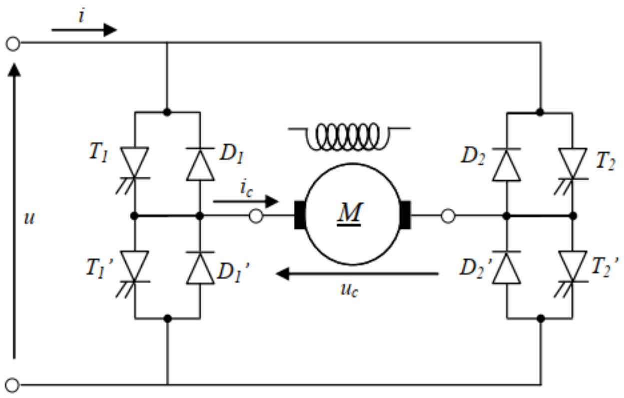


Figure. III. 25 : A bridge chopper is used for controlling DC motors

Four-Quadrant Operation:

The H-Bridge chopper, made up of four switches (T1, T2, T3, T4) and four free-wheeling diodes (D1, D2, D3, D4), allows a DC motor to operate in all four quadrants (forward motoring, reverse motoring, forward braking, and reverse braking). Below are the different operation modes of an H-Bridge:

1. Forward Motoring (Quadrant 1)

- **Switches ON**: T1 and T4 are ON.
- **Current Direction**: From the positive terminal of the supply through T1, into the motor, out through T4, and back to the negative terminal of the supply.
- **Motor Action**: The motor operates in the forward direction, with both voltage and current positive.

This is normal **motoring** mode for the forward direction, where the motor accelerates and drives the load.

2. Forward Braking (Quadrant 2)

- **Switches ON**: T2 and T3 are OFF, allowing free-wheeling through diodes D2 and D3.
- **Current Direction**: The current reverses its path back through the supply, flowing through D2 and D3.

- **Motor Action**: The motor acts as a generator, feeding energy back into the supply, and braking while the current remains positive.

This is **regenerative braking** mode for the forward direction, where the motor slows down while energy is recovered.

3. Reverse Motoring (Quadrant 3)

- **Switches ON**: T2 and T3 are ON.
- **Current Direction**: From the positive terminal of the supply through T2, into the motor, out through T3, and back to the negative terminal of the supply.
- **Motor Action**: The motor operates in reverse, with both voltage and current negative.

This is normal **motoring** mode for the reverse direction, where the motor drives the load in the reverse direction.

4. Reverse Braking (Quadrant 4)

- **Switches ON**: T1 and T4 are OFF, allowing free-wheeling through diodes D1 and D4.
- **Current Direction**: The current flows through diodes D1 and D4, returning energy to the supply.
- **Motor Action**: The motor acts as a generator in reverse, braking while the current is negative and the voltage is positive.

  This is **regenerative braking** mode for the reverse direction, where the motor decelerates and recovers energy.

The summary of operation in table

Mode	Switches ON	Voltage	Current	Operation
Forward Motoring	T1, T4	Positive	Positive	Driving load forward
Forward Braking	D2, D3 (free-wheeling)	Negative	Positive	Regenerative braking forward
Reverse Motoring	T2, T3	Negative	Negative	Driving load in reverse
Reverse Braking	D1, D4 (free-wheeling)	Positive	Negative	Regenerative braking in reverse

Advantages of an H-Bridge Chopper:

1. **Four-Quadrant Operation**:
   - Allows the motor to operate in **all four quadrants**: forward motoring, reverse motoring, forward braking (regenerative), and reverse braking.
2. **Bidirectional Control**:
   - Provides **bidirectional** control of both current and voltage, allowing the motor to run in both forward and reverse directions.

3. **Energy Recovery**:
   - Capable of **regenerative braking**, meaning it can return energy to the power source during braking, improving system efficiency.
4. **Smooth Speed Control**:
   - Enables smooth and precise **speed control** of DC motors over a wide range of operating conditions.
5. **Versatility**:
   - Can be used in a variety of applications, including electric vehicles, industrial machinery, and robotic systems, where precise and efficient motor control is necessary.

Disadvantages of an H-Bridge Chopper:

1. **Complexity**:
   - The circuit is **more complex** than simpler single- or two-quadrant choppers due to the need for four switches and additional control logic to manage operation.
2. **Cost**:
   - Due to the higher number of components, including switches (T1, T2, T3, T4) and diodes, the **cost** is higher compared to simpler chopper circuits.
3. **Switching Losses**:
   - The more frequent switching of four transistors can lead to **higher switching losses**, affecting overall efficiency, especially at higher frequencies.
4. **Control Circuit Complexity**:
   - Requires a more **sophisticated control circuit** to properly manage the switching sequences for four quadrants, increasing the difficulty of design and implementation.
5. **EMI Issues**:
   - The switching of large currents and voltages can generate significant **electromagnetic interference (EMI)**, requiring proper filtering and shielding.

H-Bridge Chopper vs. Dual Converter

A comparison between an H-Bridge Chopper and a Dual Converter when driving a DC motor:

Feature	H-Bridge Chopper	Dual Converter
Quadrant Operation	Operates in **four quadrants**: forward motoring, reverse motoring, forward braking (regenerative), and reverse braking.	Operates in **four quadrants**: forward motoring, reverse motoring, forward braking (regenerative), and reverse braking.
Number of Switches	Requires **four switches** (T1, T2, T3, T4) and four free-wheeling diodes.	Requires **two sets of converters** (each with a set of switches, typically thyristors or transistors).
Control Complexity	**Moderately complex** control due to the need to manage four switches and their sequences.	**More complex** due to the need to control two separate converters and manage their operation for bidirectional control.
Regenerative Braking	**Supports regenerative braking** in both forward and reverse directions, which improves energy efficiency.	**Supports regenerative braking** by allowing bidirectional current flow through the converters, enabling energy recovery in both directions.
Switching Losses	**Higher switching losses** due to the continuous operation of four switches.	**Lower switching losses** in each converter compared to the H-Bridge, but overall system losses can vary depending on the converters' design.
Efficiency	Generally efficient for small to medium power applications, but can be less efficient in high-power applications due to switching losses. s.	Typically more efficient for high-power applications, as dual converters can manage power flow more effectively and handle higher current
Applications	Well-suited for **small to medium power applications** like robotics, electric vehicles, and small industrial machines.	Ideal for **high-power applications** such as large industrial motors, electric vehicles, and systems requiring precise control and energy recovery.

- **H-Bridge Chopper**: Suitable for applications where precise control in all four quadrants is required but may be limited by complexity and switching losses in higher power scenarios.
- **Dual Converter**: Better suited for high-power applications and offers efficient control in all four quadrants with potentially lower switching losses, though it is more complex in terms of control and system design.

Choosing between the two depends on the power requirements, efficiency needs, and the complexity of the control system in your application.

Chapter IV

Speed Control of Induction Motors

IV.1 Introduction :

Induction motors, also known as asynchronous motors, are widely used in various industrial and commercial applications due to their robustness, simplicity, and cost-effectiveness. Speed control of induction motors is crucial for optimizing performance, energy efficiency, and operational flexibility. This chapter covers different methods for controlling the speed of induction motors, including their principles, advantages, and applications.

IV.2 Recap on Induction Motors :

Machine Construction

An induction motor primarily consists of the following components:

1. **Stator**:
   - **Construction**: Made up of laminated magnetic sheets and includes a three-phase winding (3Φ) connected to the power supply.
   - **Function**: The stator generates a rotating magnetic field that magnetizes the air gap between the stator and rotor.
2. **Rotor**:
   - **Construction**: Composed of stacked laminated magnetic sheets mounted on the motor shaft, and it carries a winding. The rotor can be of two types:
     - **Squirrel-Cage Rotor**: The most common type, where the rotor bars are shorted at the ends by end rings, forming a "cage" structure.
     - **Wound Rotor**: Contains windings similar to the stator, which are connected to external resistors or other control devices.

Operation:

The **operating principle** of an induction motor is based on the electromagnetic interaction between the stator's rotating magnetic field and the induced currents in the rotor:

- **Electromagnetic Interaction**: When the stator winding is energized with three-phase current, it produces a rotating magnetic field. This field induces a current in the rotor due to electromagnetic induction.
- **Torque Generation**: The interaction between the rotating magnetic field and the induced current in the rotor generates a torque. This torque causes the rotor to turn, producing mechanical motion.

.

IV.3 Equivalent Circuit of an Induction Motor:

In induction machines, similar to transformers, the rotor winding is often referred to as the secondary winding. To analyze the motor's performance, the rotor winding's parameters are transformed to the stator side, while keeping the actual energy relationships within the machine unchanged.

Equivalent Circuit Models

1. **T-Circuit Model**

   ○ **Description**: The T-circuit model is used to represent the induction motor's equivalent circuit. This model accounts for the variations in load and the resulting changes in currents in both the rotor and stator circuits, as well as the magnetizing branch. **Figure IV.1** shows the T-equivalent circuit of the induction motor. In this model, the motor's behavior under varying load conditions is represented, with changes in rotor and stator currents and the magnetizing branch.

   ○ **Features**:

   ▪ Load variation affects the current in both the rotor and stator circuits.

   ▪ The magnetizing current Im is not considered constant and varies with load changes.

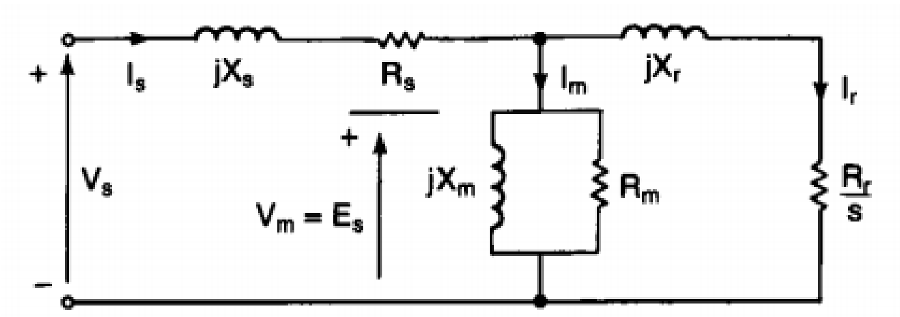


Figure. IV. 1 : The T-equivalent circuit of the induction motor.

2. **L-Circuit Model**

▪ **Description**: The L-circuit model simplifies the representation of the induction motor by assuming the magnetizing current Im to be constant and effectively zero, regardless of the load. **Figure IV.2** shows the L-equivalent circuit of the induction motor. This model provides a simplified view where Xm (the reactance of the magnetizing branch) is much larger compared to other impedances, allowing the assumption Im≈0.

○ **Features**:

▪ The magnetizing current Im is considered negligible, making it easier to analyze the motor's performance.

▪ The current in the stator Is can be approximated as equal to the current in the rotor Ir, simplifying calculations.

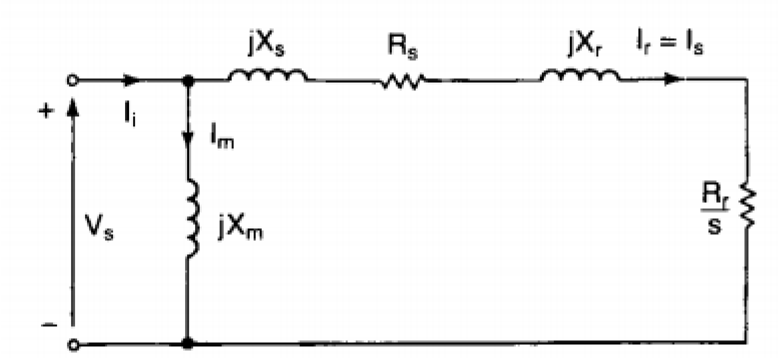


Figure. IV. 2 : The L-equivalent circuit of the induction motor.

IV.4 Power Balance of the Induction Motor:

Notation:

- Ir : Rotor current
- Is : Stator current

Figure IV. 3 represente the Power Balance of the Induction Motor

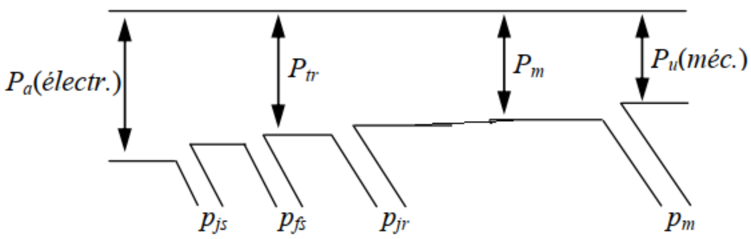


Figure. IV. 3 : Power Balance of the Induction Motor.

Power Losses

Stator Copper Losses is :

$$P_{js} = 3{I_s}^2 . R_s \qquad (IV.\ 1)$$

Where Rs is the stator resistance.

Rotor Copper Losses is :

$$P_{jr} = 3{I_r}^2 . R_r \qquad (IV.\ 2)$$

Where Rr is the rotor resistance.

Core losses are predominantly in the stator and are negligible in the rotor:

$$P_c = \frac{3{V_s}^2}{R_m} \qquad (IV.\ 3)$$

Where Vs is the stator voltage and Rm is the magnetizing reactance.

Electromagnetic Power is:

$$P_{em} = T_{em} . \Omega_s \qquad (IV.\ 4)$$

Where T_{em} is the electromagnetic torque and Ωs is the synchronous speed.

The electromagnetic power Pem is:

$$P_{em} = P_m + p_{jr} + p_{add=0} \quad (IV.\ 5)$$

p_{add} are any additional losses (often assumed to be zero).

$$p_{jr} = P_{em} - P_m = T_{em}.\Omega_s - T_{em}.\Omega_r = T_{em}.(\Omega_s - \Omega_r).\frac{\Omega_s}{\Omega_s} \quad (IV.\ 6)$$

$$p_{jr} = T_{em}.\Omega_s.\frac{(\Omega_s - \Omega_r)}{\Omega_s} = P_{em}.S \quad (IV.\ 7)$$

Where S is the slip.

Therefore: $P_{em} = \frac{P_{jr}}{S} = 3{I_r}^2.\frac{R_r}{S}$ (IV. 8)

The mechanical power output is the electromagnetic power minus rotor losses

$$P_m = P_{em} - p_{jr} = P_{em} - P_{em}.S \quad (IV.\ 9)$$

Mechanical Power:

$$P_m = P_{em}(1 - S) \quad (IV.\ 10)$$

Developed Torque: $T_d = \frac{P_m}{\Omega_r} = \frac{P_m}{\Omega_s(1-S)}$ (IV. 11)

the efficiency $\boldsymbol{\eta}$ of the motor is:

$$\boldsymbol{\eta} = \frac{P_{out}}{P_{in}} = \frac{P_{em}(1-S)}{P_{em}+\sum pert} \quad (IV.\ 12)$$

When electromagnetic power

$$P_{em} \gg p_j + p_f \quad (IV.\ 13)$$

The efficiency becomes:

$$\boldsymbol{\eta} = \frac{P_{em}(1-S)}{P_{em}} \quad (IV.\ 14)$$

$$\boldsymbol{\eta} = (1 - S) \quad (IV.\ 15)$$

IV.5 Calcule de couple à partir du schéma équivalent en L :

The input impedance Z_e is given by:

$$\frac{1}{Z_e} = \frac{1}{Z_1} + \frac{1}{Z_2} = \frac{Z_1+Z_2}{Z_1\ .\ Z_2} \quad (IV.\ 16)$$

Where : $\begin{cases} Z_1 = \left(R_s + \frac{R_r}{S}\right) + j(\,X_s + X_r\,) \\ Z_2 = j\,X_m \end{cases}$ (IV. 17)

Thus, the overall impedance becomes:

$$Z_e = \frac{-X_m(\,X_s+X_r\,)+j\,X_m\left(R_s+\frac{R_r}{S}\right)}{\left(R_s+\frac{R_r}{S}\right)+j(\,X_s+X_r+X_m\,)} \quad (IV.\ 18)$$

The rotor current I_r can be calculated as:

$$I_r = \frac{V_s}{Z_1} = \frac{V_s}{\sqrt{\left(R_s+\frac{R_r}{S}\right)^2+(X_s+X_r)^2}} \quad (IV.\ 19)$$

Using the rotor current, the electromagnetic power is given by:

$$P_{em} = 3I_r^2.\frac{R_r}{S} = \frac{3\,R_rV_s^2}{S[\left(R_s+\frac{R_r}{S}\right)^2+(X_s+X_r)^2]} \quad (IV.\ 20)$$

And : $P_{em} = T_{em}\,.\Omega_s \Rightarrow T_{em} = \frac{P_{em}}{\Omega_s}$ (IV. 21)

Finally, the torque developed by the motor is:

$$T_{em} = \frac{3\,R_rV_s^2}{S\Omega_s[\left(R_s+\frac{R_r}{S}\right)^2+(X_s+X_r)^2]} \quad (IV.\ 22)$$

IV.6 Mechanical Characteristic of the Induction Motor

When an induction machine is powered by a fixed voltage source, the electromagnetic torque T_{em}becomes a function of the slip g and consequently of the speed. The mechanical characteristic, $T_{em} = f(g)$ or $T_{em} = f(N)$, can be illustrated as shown in **Figure IV.4**.

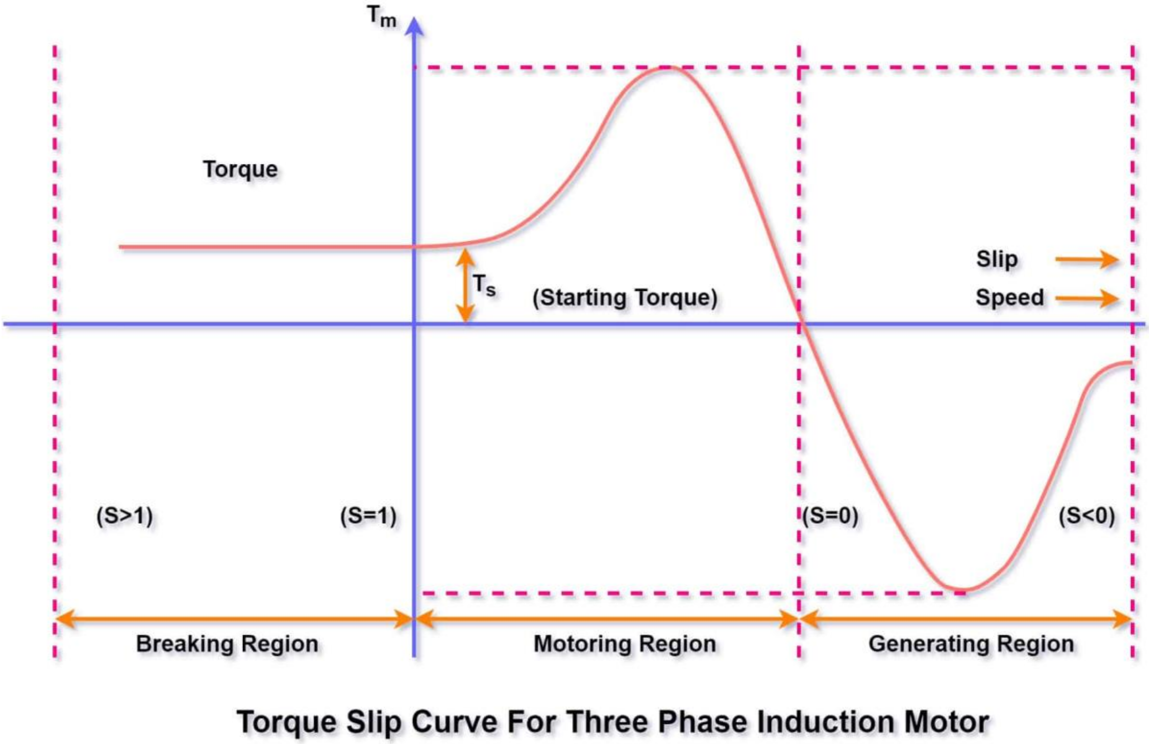


Figure. IV. 4 : Torque slip curve for three phase induction machine**.**

- At startup, the motor speed is zero ($\Omega = 0$), which corresponds to a slip S=1. The starting torque can be calculated as follo :

$$T_{emS} = \frac{3\,R_rV_s^2}{\Omega_s[(R_s+R_r)^2+(X_s+X_r)^2]} \quad (IV.\ 23)$$

- The slip for maximum torque is obtained by setting $\frac{dT_{em}}{dS} = 0$, which gives:

$$S_{Tmax} = \frac{\pm R_r}{\sqrt{R_s^2+(X_s+X_r)^2}} \quad (IV.\ 24)$$

Where : $+$ *corresponds to motor operation*
$-$ *corresponds to generator operation*

By substituting S_{Tmax} into the torque equation, the maximum electromagnetic torque is given by :

$$T_{em_{max}} = \frac{3\,{V_s}^2}{2\,\Omega_s[\pm R_s + \sqrt{{R_s}^2 + (X_s + X_r)^2}]} \quad \text{(IV. 25)}$$

- If we neglect the value of R_s compared to the other impedances, the electromagnetic torque equation simplifies to: :

$$T_{em} = \frac{3\,R_r {V_s}^2}{S\Omega_s[\left(\frac{R_r}{S}\right)^2 + (X_s + X_r)^2]} \quad \text{(IV. 26)}$$

The simplified starting torque equation becomes :

$$T_{emd} = \frac{3\,R_r {V_s}^2}{\Omega_s[(R_r\,)^2 + (X_s + X_r)^2]} \quad \text{(IV. 27)}$$

The slip at maximum torque in this case is:

$$S_{Tmax} = \frac{\pm\,R_r}{X_s + X_r} \quad \text{(IV. 28)}$$

The simplified maximum torque equation becomes:

$$T_{em_{max}} = \frac{3\,{V_s}^2}{2\,\Omega_s[X_s + X_r]} \quad \text{(IV. 29)}$$

We can define the ratio $\frac{T_{em}}{T_{em_{max}}}$ e using the formulas above:

$$\frac{T_{em}}{T_{em_{max}}} = \frac{2 \cdot S \cdot S_{Tmax}}{S^2 + {S_{Tmax}}^2} = \frac{2R_r(X_s + X_r)}{S[\left(\frac{R_r}{S}\right)^2 + (X_s + X_r)^2]} \quad \text{(IV. 30)}$$

Similarly, the starting torque ratio can be expressed as:

$$\frac{T_{emd}}{T_{em_{max}}} = \frac{2 \cdot S_{Tmax}}{{S_{Tmax}}^2 + 1} = \frac{2R_r(X_s + X_r)}{(R_r)^2 + (X_s + X_r)^2} \quad \text{(IV. 31)}$$

If the motor operates at a small slip $S \ll 1$ and $S^2 \ll {S_{Tmax}}^2$ the electromagnetic torque becomes proportional to slip, and the torque equation simplifies to:

$$\frac{T_{em}}{T_{em_{max}}} = \frac{2 \cdot S}{S_{Tmax}} = \frac{2(\Omega_s - \Omega\,)}{S_{Tmax}\,.\Omega_s} \quad \text{(IV. 32)}$$

- The speed of the motor as a function of torque is:

$$\Omega = \Omega_s \left(1 - \frac{S_{Tmax}}{2\,T_{em_{max}}} T_{em}\right) \quad \text{(IV. 33)}$$

- From equations **IV.32** and **IV.33**, we can observe that when the motor operates at low slip, the electromagnetic torque is proportional to slip, and the speed decreases as the torque increases.

IV.7 Speed Variation of Induction Motors:

The speed and torque of an induction motor can be controlled by adjusting the following parameters :

1. Pole Number Variation.
2. Stator Voltage Control.
3. Rotor Resistance Control (R_r).
4. Stator Frequency Control.
5. Voltage and Frequency Control ($\frac{U}{f} = cst$).
6. Stator Current Control.
7. Control of Current, Voltage, and Stator Frequency.

IV.7.1 Pole Number Variation :

This method of speed control is based on changing the number of magnetic poles in the stator winding. It offers discrete speed settings according to the synchronous speed equation: (Ns=120·f/P). It is possible to obtain discrete speed variations by using two independent stator windings housed in the same slots. By switching between these windings, different synchronous speeds can be achieved.

However, this method is typically avoided because each speed corresponds to only half of the copper being used. This results in increased external dimensions of the machine (due to increased inductance losses), leading to lower efficiency.

Advantages of Pole Number Variation:

1. **Simple Control**: Pole number variation offers a simple way to adjust the speed of an induction motor without requiring complex electronic controllers.
2. **Cost-Effective for Fixed Speed Applications**: It is a relatively inexpensive method for applications where only a few discrete speed settings are needed.
3. **No Electronic Components**: This method doesn’t rely on sensitive electronics, making it more robust and reliable in harsh environments.
4. **No Harmonic Distortion**: Since no electronic switching is involved, it avoids the generation of harmonics that can negatively impact power quality.

Disadvantages of Pole Number Variation:

1. **Limited Speed Options**: The number of available speeds is limited to a small number of discrete steps, making it unsuitable for applications requiring fine or continuous speed control.

2. **Larger Motor Size**: Motors designed for pole-changing require more complex windings, which can increase the size and weight of the motor.
3. **Inefficient Use of Windings**: Only part of the stator windings is used at each speed setting, which can result in reduced efficiency and higher energy consumption.
4. **Lower Efficiency at Non-Nominal Speeds**: The efficiency of the motor can drop significantly when operating at speeds that deviate from its design optimum.
5. **Mechanical Complexity**: Switching between poles may require mechanical switches or relays, which introduces wear and can lead to maintenance issues over time.

IV.7.2 Stator Voltage Control :

Stator voltage control is one of the simplest methods for varying the speed of an asynchronous motor. This method involves keeping the frequency constant while adjusting the voltage applied to the motor. Since the torque is proportional to the square of the stator voltage Vs, both the torque and the maximum torque increase with the voltage.

The ratio $\frac{T}{T_n}$ gives an estimate of the torque increase:

$$\frac{T}{T_n} = \frac{S}{S_n}\left(\frac{V_s}{V_{sn}}\right)^2 \qquad (IV.\ 34)$$

Where T_n is the torque at nominal voltage.

Reducing the stator voltage results in a decrease in speed, and this relationship can be observed in the motor's mechanical characteristics, represented graphically below (Figure IV.5). For squirrel cage motors, a significant reduction in stator voltage will eventually push the motor into an unstable operating region, limiting the range of speed variation.

Applications of Stator Voltage Control:

- When the load torque is not constant.
- For low-starting torque applications.

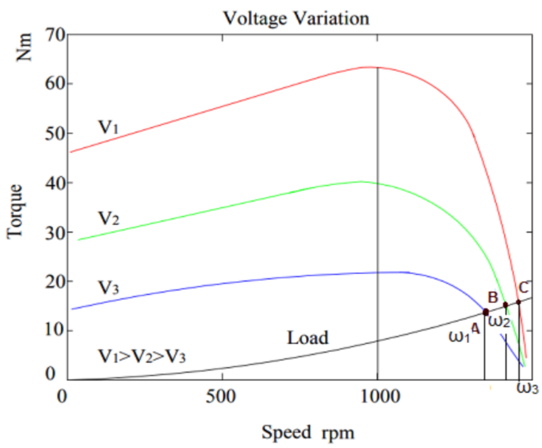


Figure. IV. 5 : speed-torque caracteristics of stator voltage controle.

Advantages of Stator Voltage Control:

1. **Simplicity**: This is one of the simplest methods to implement for speed control of asynchronous motors.
2. **Cost-Effective**: It requires minimal components compared to more complex speed control methods.
3. **Low Starting Torque Applications**: Suitable for applications where the motor requires low starting torque, such as fans, pumps, and other low-load devices.
4. **Smooth Speed Variation**: Offers gradual and smooth control of motor speed within a limited range.
5. **Energy Savings at Low Loads**: Reducing voltage under low load conditions can lead to energy savings.

Disadvantages of Stator Voltage Control:

1. **Limited Speed Range**: Speed variation is limited and becomes less effective at higher speeds due to the unstable operating region when voltage is reduced too much.
2. **Low Efficiency**: The motor operates less efficiently at lower voltages due to increased losses in the motor's stator and rotor.
3. **Reduced Torque**: As the voltage decreases, the torque output reduces significantly, which may be inadequate for applications that require high starting torque.
4. **Mechanical Stress**: Frequent voltage variations can induce mechanical stress in the motor, potentially shortening its lifespan.

IV.7.2.1 Methods for Controlling Stator Voltage

IV.7.2.1.A Three-Phase Autotransformer

A three-phase autotransformer is commonly used to control the stator voltage of an asynchronous (induction) motor by stepping down the supply voltage. This method allows for a smooth and gradual change in the motor's voltage, which directly affects the speed and torque of the motor. The autotransformer is connected to the motor in a star (Y) or delta (Δ) configuration, depending on the motor's design.

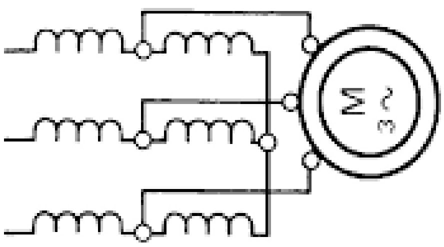


Figure. IV. 6 : Three-Phase Autotransformer for Controlling Stator Voltage.

Working Principle:

- **Voltage Regulation**: The autotransformer adjusts the voltage applied to the stator windings by altering the turns ratio of its coils. By reducing the voltage supplied to the motor, the speed and torque of the motor decrease.
- **Magnetic Coupling**: Unlike a full transformer, an autotransformer shares a portion of its winding between the primary and secondary circuits, which makes it more efficient in terms of energy use for voltage regulation.
- **Continuous Speed Control**: The voltage can be continuously varied, allowing for smooth speed adjustment within the operating limits of the motor.

Advantages:

1. **Sinusoidal Output Voltage**: The autotransformer provides a nearly sinusoidal voltage to the motor, which ensures smooth operation without introducing significant harmonic distortions.
2. **Energy Efficient**: Compared to traditional transformers, autotransformers are more energy-efficient because they use less copper and have lower power losses.
3. **Cost-Effective**: Since autotransformers use shared windings, they are smaller and cheaper than full transformers.
4. **Simple Operation**: The control mechanism is straightforward, providing a practical solution for speed variation.

Disadvantages:

1. **Bulky Size**: Autotransformers can be large and heavy due to the magnetic core and copper windings, which increases the overall weight of the control system.
2. **Limited Speed Control Range**: The speed control range is limited to voltage reductions. High precision control, especially at low speeds, is not achievable with this method.
3. **Fixed Tap Settings**: Most autotransformers provide voltage adjustments in discrete steps rather than continuous regulation, limiting fine control over motor speed.
4. **No Regeneration Capability**: This method does not allow for power recovery during braking or deceleration, which is a disadvantage in applications requiring frequent stops and starts.

IV.7.2.1.B Three phase AC Regulator :

A **thyristor-based gradator** (or **AC Regulator**) is an electronic device used to control the stator voltage of an asynchronous (induction) motor by adjusting the conduction angle of thyristors in each phase(Figure IV.7).

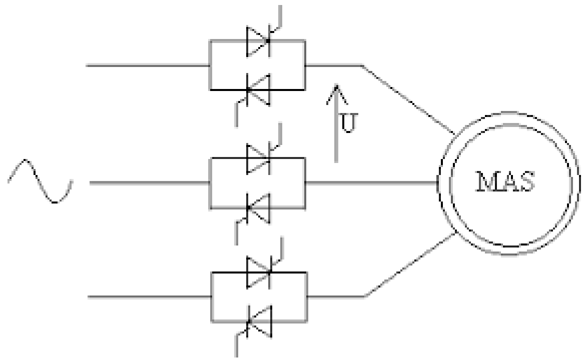


Figure. IV. 7 : Three phase AC Regulator for Controlling Stator Voltage.

Advantages:

1. **Simplicity**: The AC Regulator is relatively simple to design and implement. It requires fewer mechanical components compared to autotransformers, making it a cost-effective solution.
2. **Compact Design**: Thyristor-based controllers are compact and take up less space compared to bulkier alternatives like autotransformers.
3. **Efficient Speed Control**: Provides speed control by reducing the voltage, which lowers the speed of the motor without significant power loss.
4. **Four-Quadrant Operation**: With appropriate design, a thyristor-based controller can operate in four quadrants, allowing for both motoring and regenerative braking.

Disadvantages:

1. **Harmonics**: The non-sinusoidal output causes harmonic distortion in the motor, which can lead to increased losses, vibrations, and noise.
2. **Poor Power Factor**: Thyristor gradators tend to have a poor power factor, especially at lower speeds, leading to inefficiencies in the power system.
3. **Limited Speed Range**: The control range is limited, and the motor’s efficiency decreases significantly at lower voltages. This is especially problematic in applications requiring large variations in speed.
4. **Excessive Heating**: Due to the harmonic content and reduced voltage, the motor tends to overheat when operating under partial loads or at lower speeds.

IV.7.3 Rotor Voltage Control:

Rotor voltage control involves inserting adjustable three-phase resistances (R_h) in series with the rotor of a wound-rotor induction motor to vary the rotor voltage V_r. This method can only be applied to motors with wound rotors (not squirrel-cage rotors). By increasing the resistance R_h, the slip increases, thus controlling the speed and torque

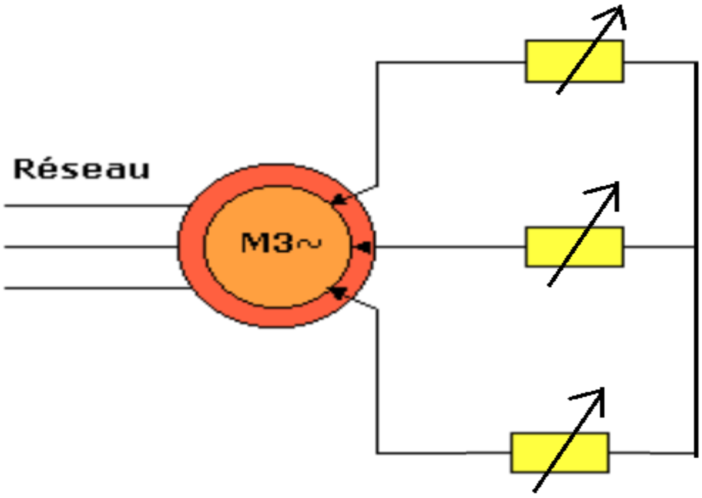


Figure. IV. 8 : commande de vitesse par rhéostat rotorique

Principle of Operation:

- In normal operation, the external resistances (R_h) are short-circuited, meaning $\boldsymbol{R_h}$ = **0**.
- By adjusting the rheostat, the resistance in the rotor circuit becomes $\boldsymbol{R_r + R_h}$ where $\boldsymbol{R_r}$ is the rotor resistance and $\boldsymbol{R_h}$ is the external resistance.
- The increase in $\boldsymbol{R_h}$ causes an increase in slip, modifying the motor's speed and torque behavior.

The slip can be adjusted as:

$$\frac{R_r}{S} = \frac{R_r+R_h}{\acute{S}} \Rightarrow \acute{S} = \frac{R_r+R_h}{R_r} S \qquad (IV.\ 35)$$

This results in an increased slip **S'** compared to the original slip **S**.

The maximum torque in a wound-rotor induction motor is indeed independent of the external resistance (*Rh*) inserted into the rotor circuit. However, increasing this resistance allows adjusting the torque curve to achieve better performance during startup.

This method is advantageous for loads requiring high starting torque. The increased resistance helps limit the inrush current, preventing electrical stress on the system.

The figure IV.9 typically illustrates how the torque-speed curve shifts based on different values of rotor resistance, showing improved starting torque with increased resistance.

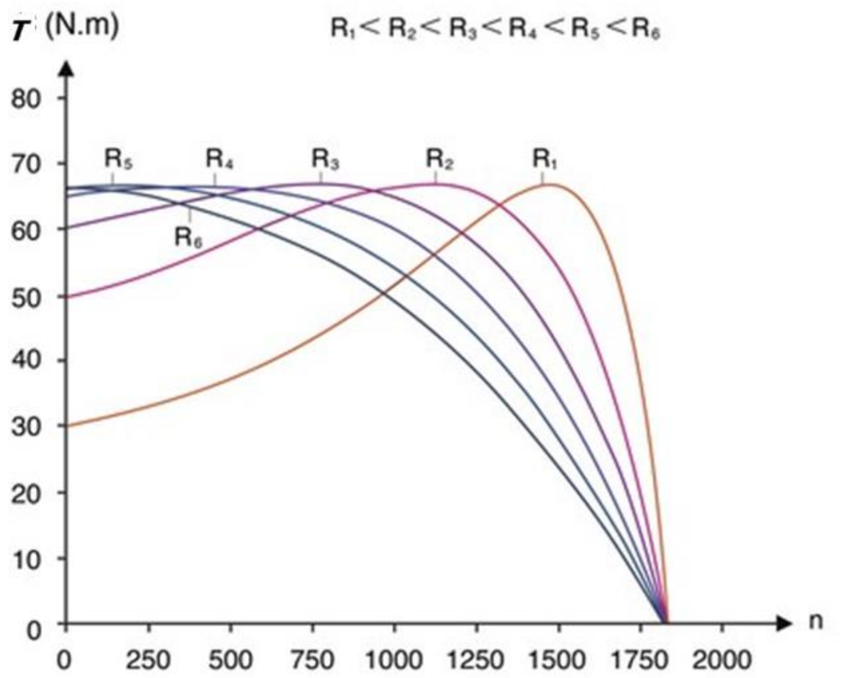


Figure. IV. 9 : Modification of Motor Characteristics by Rotor Rheostat Insertion

Advantages of Rotor Resistance Control:

1. **High Starting Torque**: Inserting adjustable resistances into the rotor circuit allows for an increase in starting torque, which is beneficial for loads that require high torque at startup.
2. **Smooth Speed Control**: This method allows smooth and gradual control of motor speed by adjusting the resistance. This makes it suitable for applications where varying speed is needed.
3. **Reduced Inrush Current**: By increasing rotor resistance, the starting current is limited, reducing the mechanical and electrical stress on the motor and the power supply system during startup.
4. **Stable Operation**: This method operates in the stable region of the torque-speed curve, making it suitable for applications with varying loads, ensuring stable performance without sudden fluctuations.
5. **Easy Implementation**: It is a relatively simple and cost-effective method for controlling the speed of wound-rotor induction motors, especially in older or lower-power applications.

Disadvantages of Rotor Resistance Control:

1. **Reduced Efficiency**: The additional resistance causes energy losses in the form of heat, leading to reduced motor efficiency. The slip energy is dissipated as heat in the external resistors.
2. **Limited Speed Range**: The speed variation is limited, as the control is only effective near synchronous speed. Significant speed reduction below synchronous speed is not achievable with this method.
3. **Heat Dissipation**: The resistors in the rotor circuit can become quite hot during operation due to energy dissipation, requiring proper cooling systems, which can add to maintenance and costs.
4. **Potential Imbalance**: If the resistors inserted in the rotor circuit are not balanced or have unequal values, this can cause voltage and current imbalances, leading to inefficient operation and possible damage to the motor.

IV.7.3.1 Other Control Methods

IV.7.3.1.A Slip Variation Using a Chopper:

In this method, the adjustable three-phase rotor resistance is replaced by a diode rectifier and a chopper, as shown in Figure IV.10.

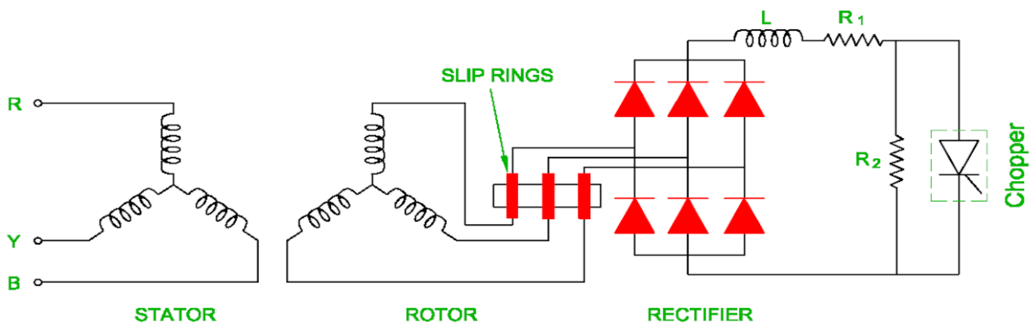


Figure. IV. 10 : Speed Control of Slip Ring Induction Motor By Chopper

Operation:

1. The AC current from the rotor is rectified by a six-diode bridge.
2. The rectified current is filtered using the inductance L_d.
3. The chopper controls the amount of power delivered to the motor by varying the duty cycle, which effectively changes the rotor resistance.

The effective resistance is given by:

$$R_h = R(1 - \gamma) \qquad (IV.\ 36)$$

Where γ is the duty cycle of the chopper. To vary the motor speed, the duty cycle is adjusted, thereby controlling the effective rotor resistance.

Advantages:

1. **Improved Efficiency**:
   - By using a chopper to control the speed, the energy is not wasted in resistors as heat, unlike in the traditional method with external resistances. This leads to higher efficiency, especially at lower speeds.
2. **Smooth Speed Control**:
   - The chopper allows for finer and continuous speed adjustment by varying the duty cycle. This provides smoother speed regulation compared to discrete control with resistors.
3. **Enhanced Torque at Low Speeds**:
   - This method maintains torque even at reduced speeds because the effective rotor resistance is modulated without excessive energy loss.
4. **Compact and Reliable**:
   - Replacing large resistors with a diode rectifier and chopper reduces the size of the control system. Additionally, power electronics-based systems (such as choppers) are more reliable and require less maintenance compared to mechanical resistors.
5. **Reduced Power Loss**:
   - The chopper dissipates less power in the form of heat as compared to traditional resistive control methods. This minimizes energy losses and improves overall system efficiency.

Disadvantages:

1. **Cost**:
   - Implementing a chopper control system involves more complex electronics (diode rectifiers, inductors, and choppers), which increases the initial cost compared to traditional resistive control.
2. **Harmonics**:
   - The rectification and chopper control introduce harmonics into the system, which may affect the motor's performance and require filtering to mitigate their effects.
3. **Complexity**:
   - The system requires a more complex control circuit and may involve additional components like inductors and filters, increasing the overall complexity of the drive system.
4. **Electromagnetic Interference (EMI)**:
   - The switching operation of the chopper can introduce electromagnetic interference, which can affect nearby electronic systems and may require shielding and filtering.
5. **Limited to Slip Ring Motors**:
   - This method can only be used with slip ring induction motors, limiting its application to a specific motor type. It cannot be applied to squirrel cage induction motors, which are more common in industrial applications.

In summary, speed control using a chopper offers better efficiency and smoother control, but at the cost of increased system complexity and potential issues with harmonics and EMI. the issue of energy dissipation in resistors remains a concern, When using external resistance, the slip energy from the rotor is dissipated as heat in the resistance. This results in energy losses and a decrease in overall efficiency, especially at low speeds where the slip is high.

IV.7.3.1.B Cascade hyposynchrone

In the hypo-synchronous cascade, the Joule losses dissipated in the resistance R can be recovered through this method.

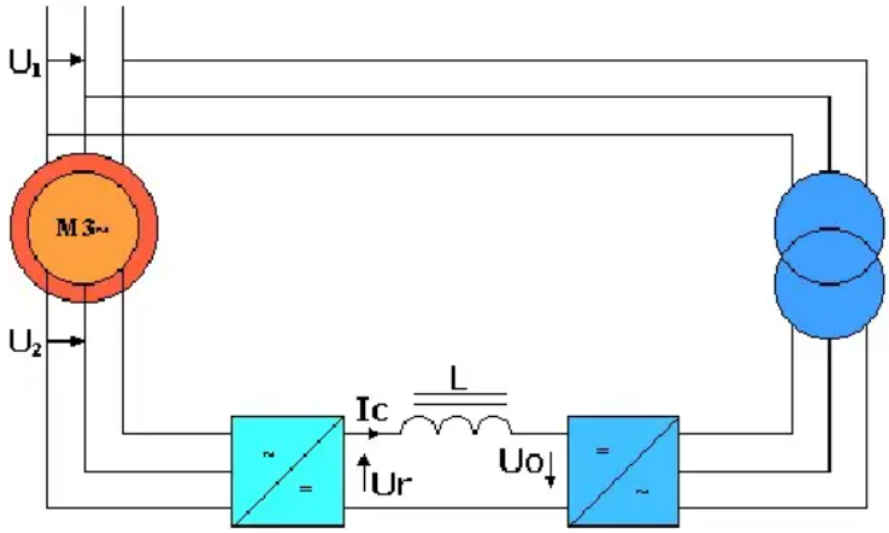


Figure. IV. 11 : The process of power recovery in a slip ring induction motor through the hyposynchronous cascade method.

The rotor of the machine is connected to a diode rectifier (Bridge PD3). The output of this rectifier is connected (with crossed poles) through a smoothing inductor L to the output of a thyristor-controlled rectifier (Bridge PD3), which operates in an **assisted inverter mode** (with a firing angle α>90∘). This inverter is powered by the three-phase grid via a transformer with a transformation ratio K2.

Explanation:

- The **diode rectifier** (PD3) rectifies the AC rotor current into DC.
- The **smoothing inductor** L smooths the DC current before it is sent to the controlled rectifier.
- The **thyristor-controlled rectifier** operates as an **inverter** when α>90∘, converting the DC back into AC to feed into the power grid.
- The **transformer** adapts the voltage levels between the inverter and the grid.

This setup allows the recovery of slip power from the rotor and its reinjection into the grid, improving the efficiency of the motor system

Advantages:

1. **Energy Recovery**:
   - **Efficiency Improvement**: This method allows for the recovery of energy that would otherwise be wasted as heat in the rotor resistors. The recovered energy

is fed back into the power grid, which enhances the overall energy efficiency of the system.

2. **Reduced Heat Losses**:
   - **Lower Heat Dissipation**: By recycling the slip energy, the method reduces the need for large external resistors, thereby minimizing heat dissipation in the resistors.
3. **High Efficiency**:
   - **Efficient Operation**: The cascade system can achieve efficiencies in the range of 90% to 95%, which is relatively high compared to traditional methods that rely solely on resistors.
4. **Power Factor Correction**:
   - **Improved Power Factor**: The inclusion of capacitors helps in correcting the power factor, which is typically lower with the cascade system alone.
5. **Reduced Operational Costs**:
   - **Cost Savings**: Over time, the energy savings from reducing resistive losses can translate into lower operational costs.

Disadvantages:

1. **Complexity**:
   - **System Complexity**: The hyposynchronous cascade system involves multiple components, including rectifiers, inverters, transformers, and inductors. This complexity can make the system more challenging to design, maintain, and troubleshoot.
2. **Initial Cost**:
   - **High Initial Investment**: The capital cost for setting up the hyposynchronous cascade system can be high due to the need for specialized equipment like inverters and transformers.
3. **Power Factor Issues**:
   - **Lower Power Factor**: The cascade itself has a lower power factor, necessitating additional equipment (capacitors) to correct it, which adds to the overall system cost and complexity.
4. **Startup Requirements**:
   - **Startup Dependency**: The system cannot start on its own and requires an external startup mechanism using rotor resistors, adding another layer of complexity.

5. **Size and Space**:
   - **Increased Space Requirement**: The additional components such as the transformer and inverter can require more space, which might be a concern in facilities with limited space.

Overall, the hyposynchronous cascade method provides significant benefits in energy recovery and efficiency but comes with challenges related to complexity, initial cost, and power factor management.

IV.7.4 Speed Control by Stator Frequency Variation:

Speed control of an induction motor can be achieved by varying the frequency of the supply voltage. The synchronous speed (Ωs) of the motor is directly proportional to the frequency of the applied voltage. By changing the frequency, you can control the motor's speed and torque characteristics.

$$\Omega_s = \beta.\Omega_b \qquad (IV.\ 37)$$

Where: Ω_b = Base synchronous speed

β = Ratio of new frequency to base frequency ($\beta < 1$)

the Slip can be calculated by:

$$S = \frac{\beta\Omega_b - \Omega_r}{\beta.\Omega_b} \qquad (IV.\ 38)$$

Electromagnetic Torque is given by:

$$T_{em} = \frac{3R_r {V_s}^2}{S\beta.\Omega_b[\left(R_s + \frac{R_r}{S}\right)^2 + (\beta.X_s + \beta.X_r)^2]} \qquad (IV.\ 39)$$

If R_s is negligible, the maximum torque at any frequency is:

$$T_{em_{max}} = \frac{3}{2.\Omega_b(X_s + X_r)} \left(\frac{V_s}{\beta}\right)^2 \qquad (IV.\ 40)$$

The slip corresponding to maximum torque is:

$$S_{Tmax} = \frac{R_r}{\beta(X_s + X_r)} \qquad (IV.\ 41)$$

The relationship between the maximum torques at different frequencies is

$$\frac{T_{em_{max}}}{T_{em_{\max b}}} = \frac{1}{\beta^2} \Rightarrow \beta = \sqrt{\frac{T_{em_{\max b}}}{T_{em_{\max}}}} \qquad (IV.\ 42)$$

Les caractéristique couple vitesse est lustré

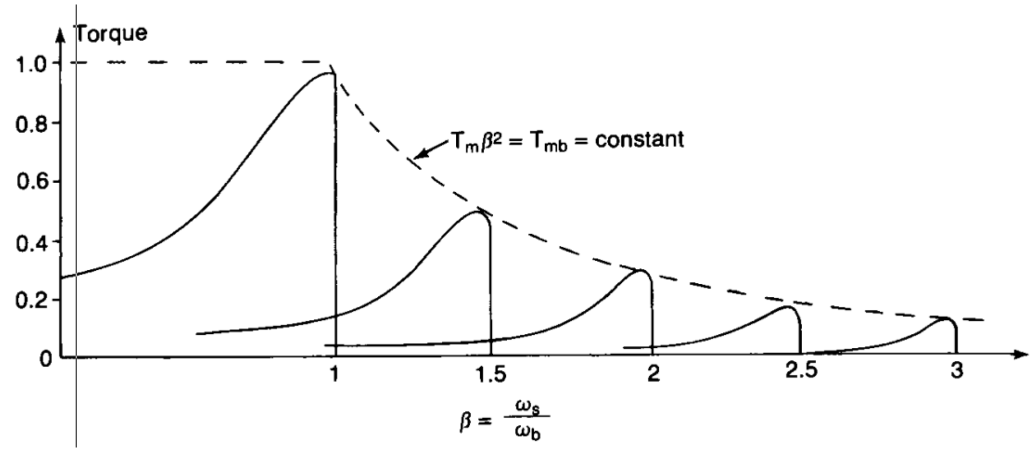


Figure. IV. 12 : Torque-Speed Characteristics with Stator Frequency Variation

According to Faraday's law for sinusoidal flux:

$$E \approx V_s \approx 4.44N\, f\, \emptyset \qquad (IV.\ 43)$$

Where:

- N is the number of turns in the winding.
- f is the frequency of the applied voltage.

Rearranging gives the flux ($\emptyset$) as:

$$\emptyset = K\frac{V_s}{f} \qquad (IV.\ 44)$$

If the voltage is kept constant and the frequency is reduced, the flux increases, potentially causing flux saturation in the air gap, which can invalidate the motor's characteristic calculations (torque/speed).

Advantages:

1. **Precise Speed Control**:
   - **Wide Range of Speeds**: The speed can be finely controlled across a wide range by varying the supply frequency. This allows for flexible operation of the motor in different applications.
2. **Improved Performance**:
   - **High Torque at Low Speeds**: By adjusting the frequency, it is possible to achieve high torque at low speeds, which is beneficial in applications requiring high starting torque.
3. **Flexibility**:
   - **Adaptability**: This method provides the ability to adjust speed and torque independently, making it suitable for variable load applications.

Disadvantages:

1. **Flux Saturation**:
   - **Saturation Issues**: Reducing the frequency increases the flux, which can lead to saturation in the air gap and make the motor parameters less accurate for torque-speed characteristics.
2. **Increased Current**:
   - **Higher Motor Currents**: Lowering the frequency can reduce the reactances (X_s, X_r , X_m), leading to increased motor currents, which might require larger equipment and affect efficiency.
3. **Complexity and Cost**:
   - **Complex Equipment**: Implementing frequency control requires additional equipment such as Variable Frequency Drives (VFDs), which can be costly and complex to maintain.
4. **Efficiency Concerns**:
   - **Potential Efficiency Losses**: At very low frequencies, the motor might operate inefficiently due to increased core losses and possible overheating.
5. **Power Factor**:
   - **Power Factor Decrease**: Frequency control can negatively affect the power factor of the motor, necessitating additional power factor correction measures.

Overall, controlling the speed of an induction motor by varying the stator frequency offers precise control and flexibility but comes with challenges related to flux saturation, increased motor currents, and the need for additional equipment.

IV.7.4.1 Speed Control Using Cycloconverter:

A cycloconverter is a device that converts an AC power supply of one frequency into an AC power supply of a different (usually lower) frequency. It is particularly useful for varying the frequency of the supply to control the speed of an asynchronous motor.

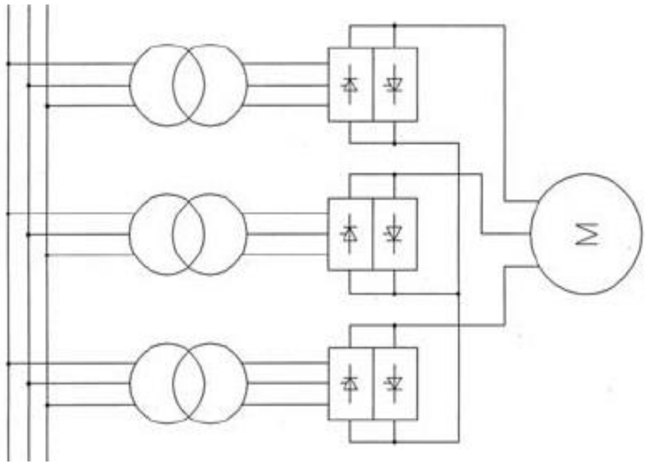


Figure. IV. 13 : Speed Control Using Cycloconverter.

Cycloconverter Operation

- **Configuration:**
  - A cycloconverter consists of three sets of converters, each powering one phase of the motor. The motor windings are isolated to allow each converter to operate independently, without being connected in a star or delta configuration.
  - The frequency and output voltage are adjusted by applying appropriate trigger pulses to the thyristors within the converters. This results in a variable-frequency output that is, on average, sinusoidal.
- **Frequency Conversion:**
  - The cycloconverter can reduce the input frequency to a maximum of 1/3 of the input frequency. For example, if the input frequency is 60 Hz, the maximum output frequency would be 20 Hz.
- **Applications:**
  - Cycloconverters are used for driving motors that operate at speeds up to about 600 rpm and can handle power levels up to 10 MW.

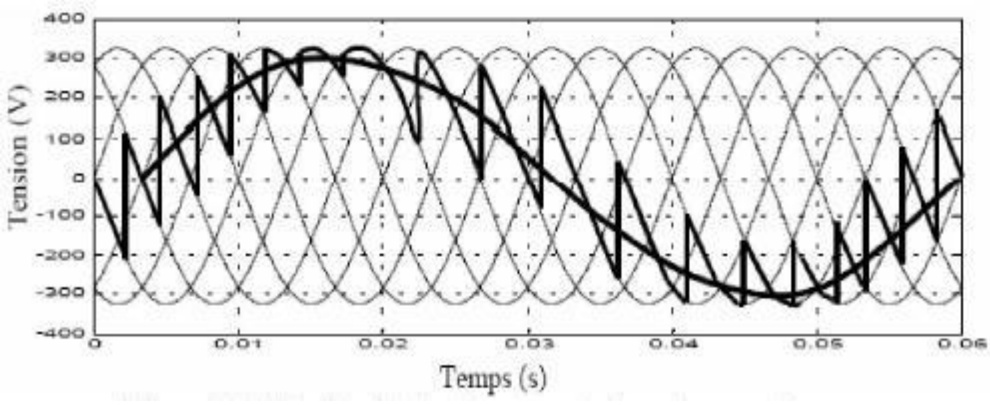


Figure. IV. 14 : Phase voltage waveform to the cycloconverter .

Advantages

1. **High Power Capability:**
   - Can handle large power levels up to 10 MW, making it suitable for high-power applications.
2. **Significant Torque at Low Frequencies:**
   - Provides substantial torque even at low frequencies, which is beneficial for applications requiring high starting torque.

Disadvantages

1. **Complexity:**
   - Requires a significant number of thyristors (typically 36), which increases the complexity of the system.
2. **Limited Frequency Range:**
   - The output frequency is limited, typically up to 20 Hz, which may restrict the range of speed control.

IV.7.5 . Speed Control by Voltage and Frequency Variation $\frac{\mathbf{V_s}}{\mathbf{f_s}} = \mathbf{cst}$ (Scalar Control) :

Scalar control, also known as Volts/Hertz control, aims to maintain a constant magnetic flux in the asynchronous motor by adjusting the voltage and frequency proportionally. This method ensures that the flux within the motor remains constant, preventing core saturation and maintaining stable operation.

$$\Phi_s = \frac{V_s}{2\pi f_s} \qquad (IV.\ 45)$$

Operation:

- To prevent flux saturation, the motor voltage must be adjusted in proportion to the frequency. This is represented by the constant voltage-to-frequency ratio: $\frac{\mathbf{V_s}}{\mathbf{f_s}}$ =constant
- **Electromagnetic Torque Calculation:** When the stator resistance R_s is negligible ($R_s \ll$), the maximum electromagnetic can be calculated as:

  $$T_{em\,max} = \frac{3{V_s}^2}{\Omega_s(X_s+X_r)} \quad \text{and} \quad \begin{cases} X = 2\pi f L \\ \Omega_s = \frac{2\pi f}{p} \end{cases} \qquad (IV.\ 46)$$

  $$T_{em\,max} = \frac{3P}{8\pi^2(L_s+L_r)}\left(\frac{V_s}{f}\right)^2 \qquad (IV.\ 47)$$

- If the frequency is adjusted such that $\Omega_s = \beta\Omega_b$ eand $\frac{V_s}{f_s} = cst$:

  $$\frac{V_s}{2\pi f_s} = D \qquad (IV.\ 48)$$

  The torque becomes::

$$T_{em} = \frac{3R_rD^2\Omega_b^2(\beta\Omega_b+\Omega_r)}{\Omega_b^2(R_s+R_r)^2+[(\beta\Omega_b+\Omega_r)(X_s+X_r)]^2} \quad (IV.\ 49)$$

- The slip for maximum torque is given by:

$$S_{Tem\,max} = \frac{R_r}{\sqrt{{R_s}^2+\beta^2(X_s+X_r)^2}} \quad (IV.\ 50)$$

Characteristics Curve: At the base frequency, the voltage is at its nominal value, which is the maximum voltage. Beyond the base frequency, since the voltage cannot be further increased, the ratio $\frac{V_s}{f_s}$ must be decreased, which results in a reduced maximum torque. This indicates operation at constant power. **Figure IV.15:** Illustrates the adjustment characteristics of the motor by Scalar Control.

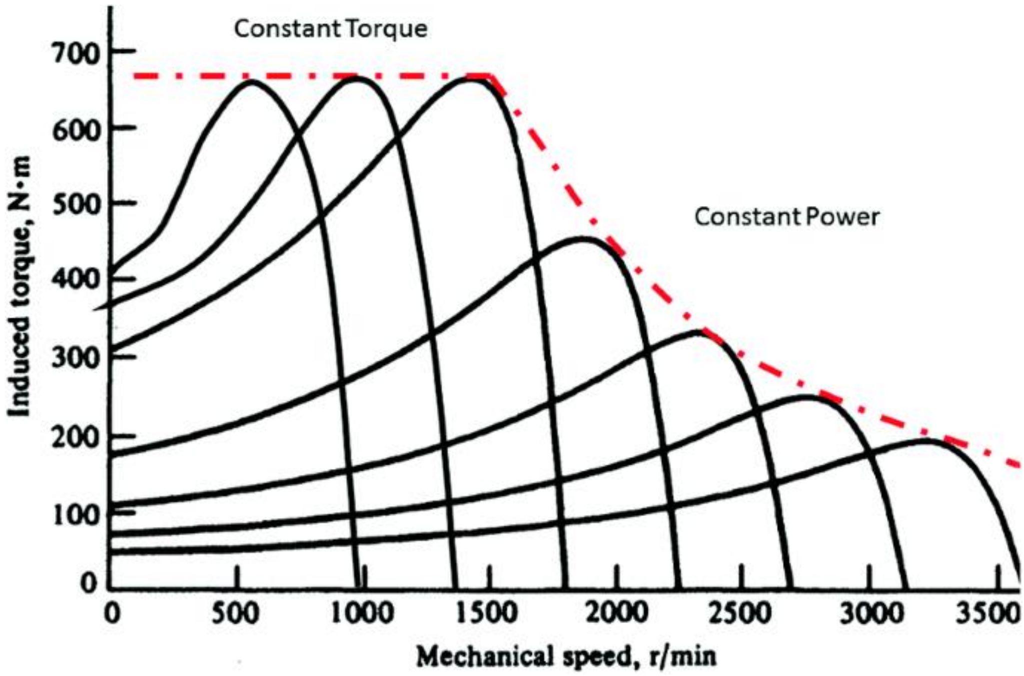


Figure. IV. 15 : the adjustment characteristics of the motor by Scalar Control

A la fréquence de base, en atteint de tension nominale (c'est la tension maximale). Au delà de fréquence de base, et puisque Vs ne peut pas être encore augmenté avec la fréquence, on doit diminuer le rapport $\frac{V_s}{f_s}$ et donc diminuer le couple max (fonctionnement à puissance constante).

Advantages:

1. **Simplicity:**
   - The method is straightforward and involves adjusting the voltage and frequency in a proportional manner.
2. **Effective for Constant Load:**

- Provides reliable speed control for applications where the load torque is constant.

3. **Cost-Effective:**
   - Often less complex and cheaper compared to more advanced control methods.

Disadvantages:

1. **Torque Reduction at Low Frequencies:**
   - Maximum torque decreases as frequency increases, since the voltage cannot be further increased after the base frequency is exceeded.
2. **Limited Speed Range:**
   - The method may not be suitable for applications requiring a wide range of speed control.
3. **Potential for Flux Saturation:**
   - If the voltage is not properly adjusted with the frequency, there is a risk of flux saturation, which can affect motor performance and efficiency.
4. **Power Factor Degradation:**
   - The power factor of the motor may degrade at lower frequencies, affecting overall efficiency.

IV.7.5.1 Methods for Variable Voltage and Frequency Control:

IV.7.5.1.A Fixed DC and PWM Inverter drive:

This method uses a non-controlled rectifier to convert AC voltage to a fixed DC voltage. The Pulse Width Modulation (PWM) inverter is then used to vary both the voltage and frequency of the output. **Figure IV. 16:** Shows the setup of a non-controlled rectifier with a PWM inverter.

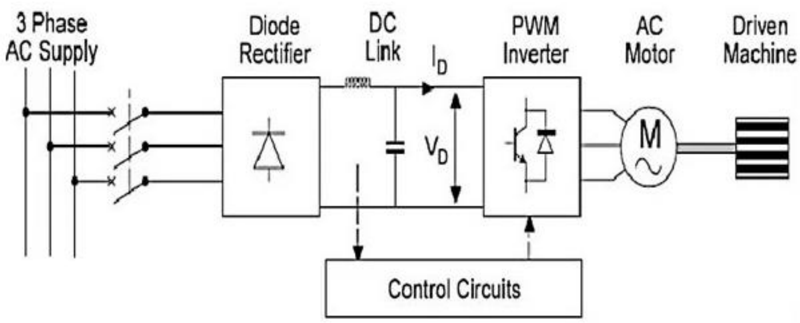


Figure. IV. 16 : Fixed DC and PWM Inverter drive.

Advantages:

- **Simplicity:** The non-controlled rectifier provides a simple means to generate a fixed DC voltage.

- **Flexibility:** The PWM inverter allows for precise control of both voltage and frequency.
- **Cost-Effective:** The combination is generally more cost-effective than other methods involving fully controlled rectifiers.

Disadvantages:

- **Fixed DC Voltage Limitation:** The fixed DC voltage may not be optimal for all applications.
- **Harmonics:** The use of PWM can introduce harmonics into the system, which may require additional filtering.

IV.7.5.1.B Variable DC and Inverter:

In this setup, a DC chopper (or DC-DC converter) is used to adjust the DC voltage level, and the inverter then varies the frequency of the output. **Figure IV. 17:** Depicts an inverter with a variable DC voltage source.

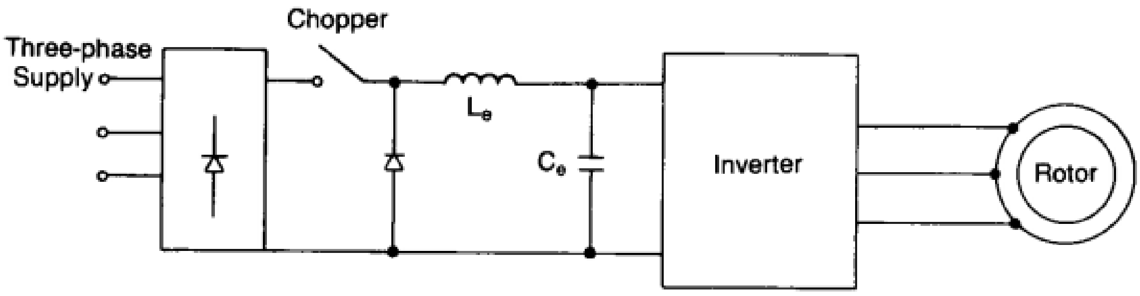


Figure. IV. 17 : Variable DC and Inverter

Advantages:

- **Versatility:** Allows for both voltage and frequency to be adjusted independently.
- **Improved Control:** Better control over the DC voltage can enhance the performance of the inverter and overall system efficiency.

Disadvantages:

- **Complexity:** The addition of a DC chopper increases system complexity and cost.
- **Efficiency:** The efficiency of the DC-DC conversion may affect the overall performance.

IV.7.5.1.C Variable DC from dual converter and inverter :

A **dual converter** paired with an **inverter** can be used to provide variable DC voltage and frequency control for AC motors, including induction motors. This method combines the benefits of a bidirectional dual converter with a frequency-controlled inverter.

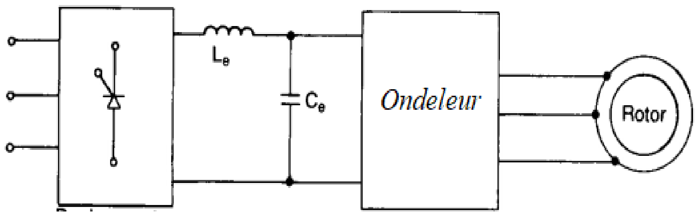


Figure. IV. 18 : Variable DC from dual converter and inverter.

Dual Converter Functionality:

- A dual converter consists of two controlled rectifiers (one for forward conversion and one for reverse conversion), allowing for bidirectional current flow.
- By adjusting the firing angles of the rectifiers, the output DC voltage can be controlled.
- This makes the dual converter a key component in applications where dynamic speed control and smooth transitions between forward and reverse directions are required.

2. Inverter for Frequency Control:

- The inverter converts the variable DC output from the dual converter into an AC signal with a variable frequency.
- The frequency of the AC output from the inverter determines the synchronous speed of the motor, and by adjusting it, the motor's speed can be controlled.

Advantages of the Dual Converter + Inverter System:

1. **Bidirectional Operation:**
   - The dual converter allows for smooth transitions between forward and reverse operation, making it ideal for applications requiring frequent direction changes, such as in electric drives.
2. **Precise Speed Control:**
   - The combination of variable DC voltage from the dual converter and frequency control from the inverter provides precise and dynamic control over motor speed.

3. **Regenerative Braking Capability:**
    - The dual converter can handle regenerative power, allowing the system to recover energy when the motor is braking, enhancing efficiency and reducing energy consumption.
4. **Improved Efficiency:**
    - Using a dual converter reduces power loss compared to resistance-based control methods. Energy dissipation is minimized since it uses controlled rectification rather than dissipating energy as heat in resistors.
5. **Flexibility:**
    - The system offers flexibility in adjusting both voltage and frequency, allowing for a wide range of speed control. This makes it suitable for high-performance applications like cranes, elevators, or large industrial motors.

Disadvantages of the Dual Converter + Inverter System:

1. **Complexity and Cost:**
    - The system requires precise control of both rectifiers in the dual converter and the inverter. This complexity increases the cost of components and control electronics.
2. **Harmonics and Filtering:**
    - The dual converter and inverter can introduce harmonics into the system, especially at lower frequencies. This may require the use of filters to ensure smooth operation.
3. **Increased Control Effort:**
    - Synchronization between the dual converter and inverter requires sophisticated control algorithms to ensure smooth performance and avoid instabilities during transitions between operating modes.
4. Low Input Power Factor at High Delay Angles:
    - In a dual converter, the output voltage is controlled by adjusting the firing (delay) angle of the thyristors or controlled rectifiers. When the firing angle is small, the rectifiers switch on earlier, resulting in a higher DC voltage.
    - At larger firing angles (closer to 90°), the rectifiers switch on later, reducing the DC voltage. However, as the firing angle increases, the input current waveform increasingly lags behind the input voltage waveform. This phase lag leads to a reduced power factor, meaning the system draws more reactive power from the grid, which is inefficient.

- At high delay angles, the input power factor can become very poor, reducing the overall system efficiency.

IV.7.6 Current Control in Induction Motors :

Current control in induction motors involves varying the rotor current to regulate torque or speed. By adjusting the stator current (I_s), the rotor current (I_r) is controlled, which directly influences the motor's performance. This control method is widely used in various industrial applications.

From the equivalent circuit model, the rotor current can be expressed as: :

$$\bar{I}_r = \frac{jX_m I_s}{R_s + \frac{R_r}{S} + j(X_m + X_s + X_r)} \quad (IV.\ 51)$$

The electromagnetic torque developed by the motor is given by:

$$T_{em} = \frac{3R_r (X_m I_s)^2}{S\Omega_s[\left(R_s + \frac{R_r}{S}\right)^2 + (X_m + X_s + X_r)^2]} \quad (IV.\ 52)$$

At startup (S=1), the starting torque is::

$$T_d = \frac{3R_r (X_m I_s)^2}{\Omega_s[(R_s + R_r)^2 + (X_m + X_s + X_r)^2]} \quad (IV.\ 53)$$

The slip at maximum torque is:

$$S_{T\,max} = \frac{\pm R_r}{\sqrt{{R_s}^2 + (X_m + X_s + X_r)^2}} \quad (IV.\ 54)$$

If stator resistance and reactance are neglected, this simplifies to:

$$S_{T\,max} = \frac{\pm R_r}{X_m + X_r} \quad (IV.\ 55)$$

At maximum slip, the maximum electromagnetic torque becomes:

$$T_{em\,max} = \frac{3\,{X_m}^2}{2\Omega_s\,(X_m + X_r)}\,{I_s}^2 = \frac{3\,{L_m}^2}{2\,(L_m + L_r)}\,{I_s}^2 \quad (IV.\ 56)$$

This demonstrates that the maximum torque ($T_{em\,max}$) is proportional to the square of the stator current ${I_s}^2$ and is relatively independent of frequency.

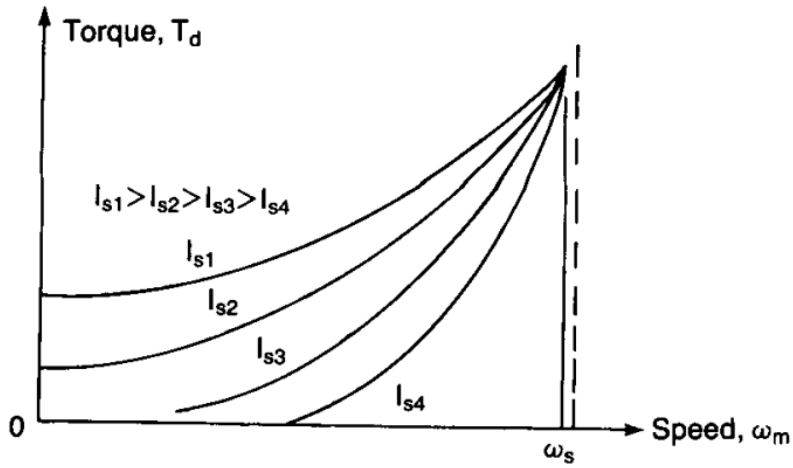


Figure. IV. 19 : Torque-speed caracteristics by current control .

Advantages of Current Control:

- **Robustness:** Current control is less sensitive to variations in motor parameters such as resistance and inductance, making it stable under changing operating conditions.
- **Precise Torque Control:** Allows for accurate regulation of torque, which is useful in various load conditions and applications.

Disadvantages of Current Control:

- **Harmonics and Torque Ripple:** Current control can introduce harmonics and torque pulsations, which can lead to vibrations and noise in the motor.
- **Complexity in Control Systems:** Implementing current control requires sophisticated control algorithms and circuitry, which can increase the complexity of the drive system.

IV.7.6.1 Current Control Methods in Induction Motors::

In current control methods, the current can be regulated using various converter configurations. Two common approaches involve current inverters fed by different types of converters.

IV.7.6.1.A Controlled rectifier-fed current source :

In this setup, an inductance serves as a current source, while the controlled rectifier adjusts the value of the DC current. The controlled rectifier effectively regulates the DC current flowing to the current-fed inverter.

The inverter then converts this controlled DC current into an AC current that is fed to the motor, allowing control over the rotor current and, hence, the motor's torque and speed.

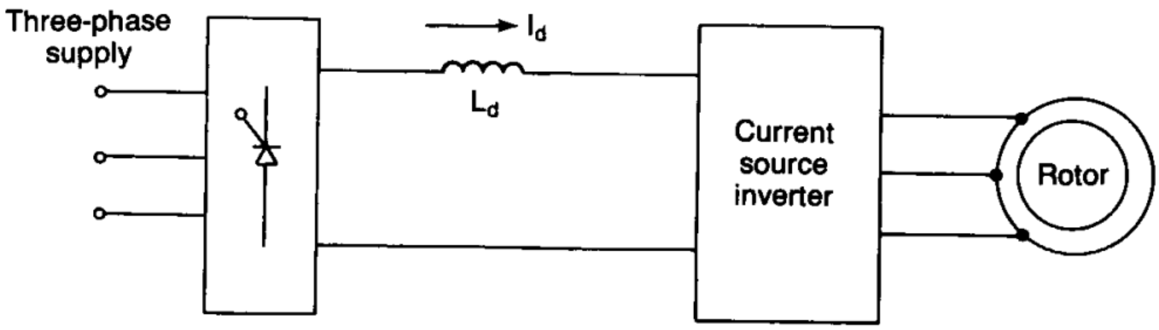


Figure. IV. 20 : Controlled rectifier-fed current source.

Advantages:

- Accurate control over the current due to the rectifier's ability to adjust the current source.
- Suitable for applications requiring stable and regulated current supply.

Disadvantages:

- Increased complexity due to the need for a controlled rectifier.
- May introduce harmonics and ripple in the current waveform, which can affect motor performance.

IV.7.6.1.B Chopper-fed current source :

In this setup, a chopper is used to regulate the current source. The chopper adjusts the DC current level, which is then fed to the current inverter to generate the necessary AC current for the motor.

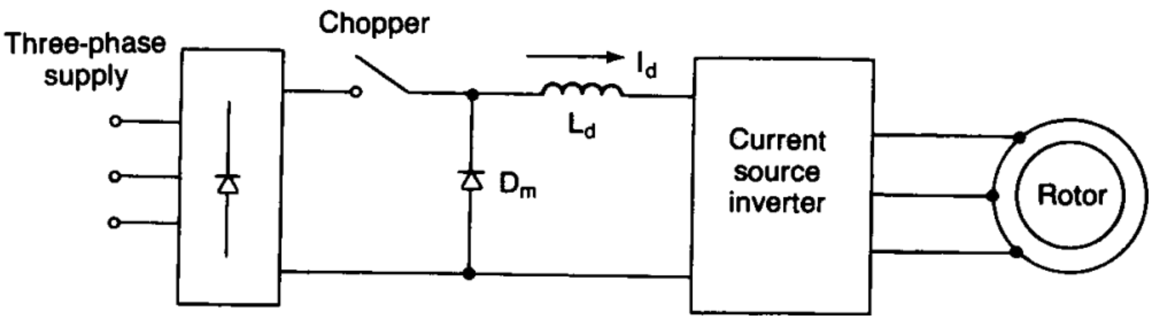


Figure. IV. 21 : Chopper-fed current source

Advantages:

- Provides fast response and dynamic control over the current.
- The chopper offers efficient regulation of the current source.

Disadvantages:

- Potential for higher switching losses due to the chopper operation.

- Complex control algorithms are needed to ensure stable operation and avoid excessive harmonics.

IV.7.7 Voltage, Current and Frequency Control :

This control method combines the advantages of each type of control—voltage, current, and frequency—to optimize performance depending on the operating region of the motor. The torque-speed characteristic is influenced by the type of control applied. The control can be divided into three distinct regions:

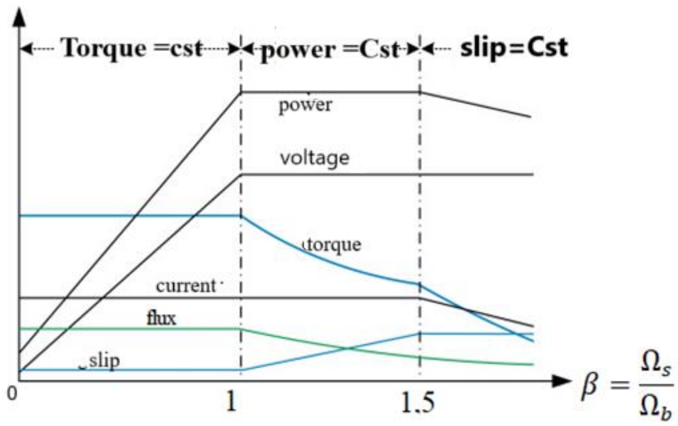


Figure. IV. 22 : Voltage, Current and Frequency Control

1st Region: Voltage Control : In this region, the speed is varied by adjusting the stator voltage while maintaining the torque constant.

2nd Region: Current Control : The motor operates at a constant current with variable slip.

3rd Region: Frequency Control : The speed is controlled by varying the stator frequency

Chapter V

Speed Variation of Synchronous Motors

V.1 Introduction :

Synchronous motors are widely used in applications that require a constant speed, regardless of the applied load. However, in some cases, there is a need to vary the speed while maintaining the motor's synchronism. This chapter discusses the various methods for speed variation of synchronous motors, focusing on the most commonly used techniques and their effects on motor performance.

V.2 Constitution of Synchronous Motors

A synchronous machine is a reversible electromechanical converter that can operate either as a generator (alternator) or as a motor:

- **As a generator (alternator)**: It generates an electrical current whose frequency is determined by the rotational speed of the machine.
- **As a motor**: It absorbs electrical current, and its rotational speed is determined by the frequency of the supplied current.

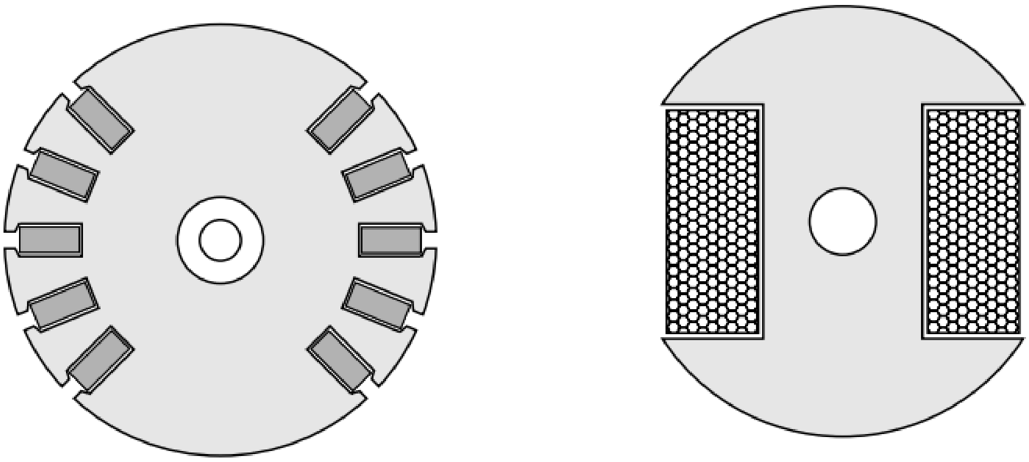
Synchronous motors consist of a polyphase winding on the stator, also known as the armature, and a field winding on the rotor, which is supplied by a DC current. The stator (armature) is similar to that of an induction machine.

Synchronous motors are constant-speed machines and always run at synchronous speed with zero slip, where the speed depends on the supply frequency and the number of poles in the motor. The synchronous speed is given by the formula:

$$n_s = \frac{120\,f}{p} \quad en \quad (rmp) \tag{V. 1}$$

The magnetic field created by the rotor can be generated in different ways:

- **Using permanent magnets**: This method is typically used for machines with power ratings up to several tens of kilowatts.
- **Using DC excitation**: A DC current flows through the field winding, creating alternating north and south poles. The rotor in this case is classified into two categories:
  - **Salient pole rotor**: Used in machines with low rotor peripheral speeds (more than 2 poles). The winding is similar to that in DC machines (an electromagnet fed by DC).
  - **cylindrical rotor**: Found in machines with high peripheral rotor speeds (1 or 2 poles). The DC winding is housed in slots cut into the cylindrical rotor body.



(a) cylindrical rotor (b) Salient pole rotor

Figure.V.1 : Two types of synchronous motor rotors

V.3 Power Balance in Synchronous Motors

The power balance in a synchronous motor is illustrated in **Figure V.2**, which shows the flow of power from the input (electrical power drawn from the grid) to the output (mechanical power transmitted to the load).

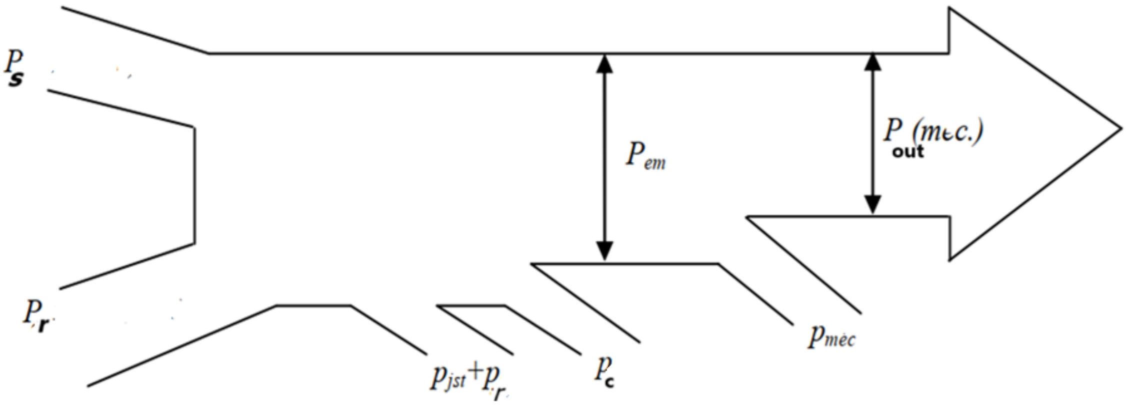


Figure.V. 2 : Power Balance in Synchronous Motors

V.4 Equivalent Circuit of cylindrical -Pole or Permanent Magnet Synchronous Machines

The field winding in synchronous machines is wound on the rotor, which is cylindrical. These motors have a uniform air gap. The equivalent single-phase circuit is presented in **Figure V.3**

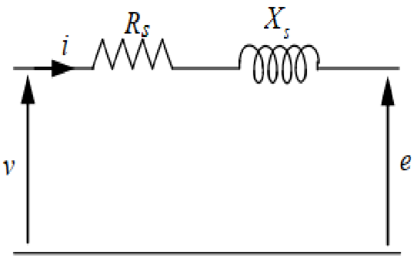


Figure.V. 3 : Single-Phase Equivalent Circuit of the Synchronous Machine.

Where:

- R_s : Resistance of one stator phase.
- $X_s = L_s\,\omega$: Synchronous reactance of the machine.
- e: Excitation voltage, dependent on the excitation current.

The equivalent circuit can be expressed by the following relation:

$$\bar{V} = (R_s + jX_s)\bar{I} + \bar{E} \quad \text{(V. 2)}$$

For R_s =0, the equation simplifies to:

$$\bar{V} = jX_s\,\bar{I} + \bar{E} \quad \text{(V. 3)}$$

his relation can be represented by the phasor diagram shown in **Figure V.4**.

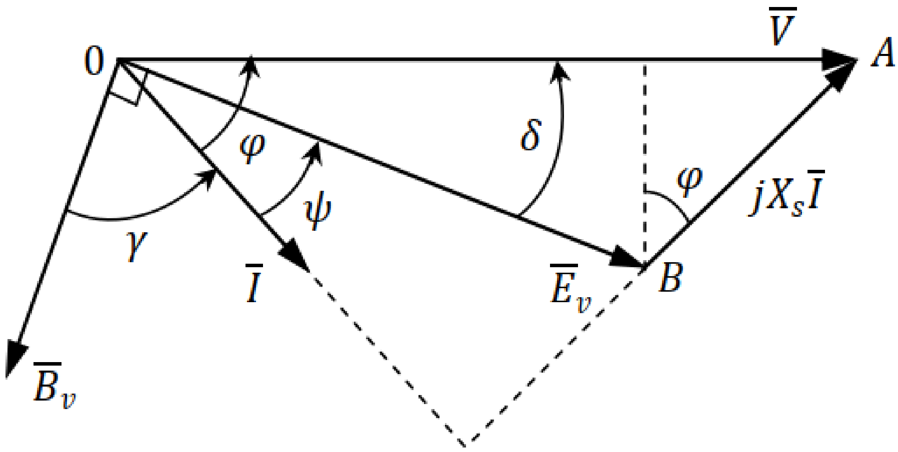


Figure.V. 4 : Phasor Diagram.

Where:

- φ: Phase shift between $\bar{I}$ and $\bar{V}$
- δ : Internal angle between $\bar{E}$ and $\bar{V}$, known as the internal angle of displacement.
- ψ: Phase shift between $\bar{I}$ and $\bar{E}$, representing the rotor's pole position relative to the stator field.

The voltage equation can also be written as:

$$\bar{V} = (R_s + jX_s)(cos\varphi - j\ sin\varphi)\ I + \bar{E} \quad \text{(V. 4)}$$

$$\bar{V} = (R_s + jX_s)(cos\varphi - j\ sin\varphi) + \bar{E} \quad \text{(V. 5)}$$

Simplifying:

$\bar{E} = V - IX_s sin\varphi - IR_s cos\varphi - jI(X_s cos\varphi - R_s sin\varphi)$ (V. 6)

Where: $\bar{E} = E\angle\delta$ (V. 7)

giving: $\delta = \tan^{-1}\frac{-(IX_s cos\varphi - IR_s sin\varphi)}{V - IX_s sin\varphi - IR_s cos\varphi}$ (V. 8)

For negligible R_s, δ becomes:

$\delta = \tan^{-1}\frac{-(IX_s cos\varphi)}{V - IX_s sin\varphi}$ (V. 9)

V.5 Torque Expressions

V.5.1 Torque as a Function of Angle ϕ\phi:

The electrical power absorbed by the motor is:

$P_a = 3VI\ cos\varphi$ (V. 10)

If we neglect resistance and core losses, this power is fully transmitted to the rotor, giving the electromagnetic power:

$P_{em} = P_a = 3VI\ cos\varphi$ (V. 11)

The torque is then:

$T_{em} = \frac{P_{em}}{\Omega_s} = \frac{3VI\ cos\varphi}{\Omega_s}$ (V. 12)

V.5.2 Torque as a Function of Angle ψ :

From the projection of the vectors $\bar{V}$ and $\bar{E}$ on the current direction:

$Vcos\varphi = E\ cos\psi$ (V. 13)

Thus, the torque becomes:

$T_{em} = \frac{3EI\ cos\psi}{\Omega_s}$ (V. 14)

Where : $E = p\Omega_s\phi_f$ (V. 15)

leading to:

$T_{em} = 3p\phi_f I\ cos\psi$ (V. 16)

This expression involves the current I, angle ψ, and flux ϕ_f , and is suitable for analysis when the machine is connected to a current-source inverter.

V.5.3 Torque as a Function of Internal Angle δ

From the phasor diagram, we have:

$X_s Icos\varphi = Esin\delta \Rightarrow\ Icos\varphi = \frac{Esin\delta}{X_s}$ (V. 17)

Hence, the torque becomes :

$$T_{em} = \frac{3VI\ cos\varphi}{\Omega_s} = \frac{3V}{\Omega_s}\ \frac{Esin\delta}{X_s} = \frac{3V}{\Omega_s}\ \frac{p\Omega_s\phi_f\ sin\delta}{X_s} = \frac{3p}{L_s}\ (\frac{V}{\omega_s})\phi_f\ sin\delta \qquad (V.\ 18)$$

This torque expression highlights three adjustable parameters :

- $\frac{V}{\omega_s}$ (controlled by the inverter).
- ϕ_f adjustable by the excitation current I_f.
- The internal angl δ (adjustable by self-piloting control).

If $\frac{V}{\omega_s}$ is constant and excitation current ϕ_f is fixed, torque is proportional to sin δ.

- if $\delta > 0 \Rightarrow T_{em} > 0$: motor operation .
- if $\delta < 0 \Rightarrow T_{em} < 0$: generator operation.
- if $\delta = \mp 90° \Rightarrow$ torque reaches its maximum, called the pull-out torque:

$$T_{em} = \frac{3V}{\Omega_s}\ \frac{E}{X_s} \qquad (V.\ 19)$$

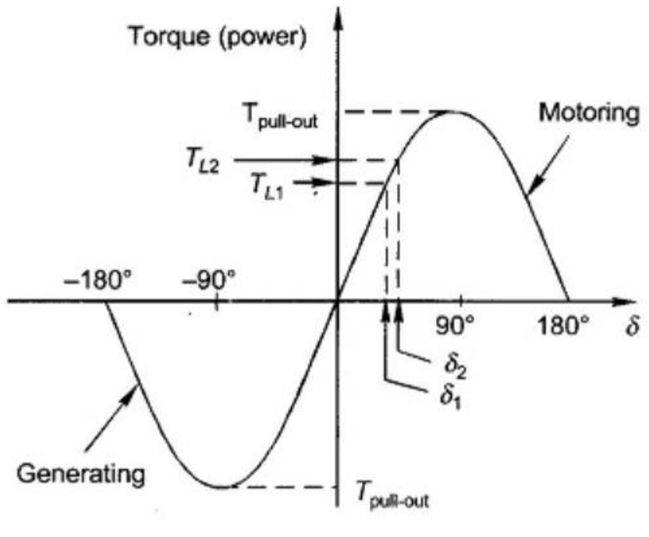


Figure.V. 5 : Torque against torque angle with cylindrical rotor

For stability, the motor operates on the positive slope of the torque characteristic, limiting the internal angle range to $-90° < \delta < 90°$.

V.6 Speed Variation in Synchronous Motors:

The synchronous motor operates at a speed defined by the equation $n_s = 120\ f/p$. To achieve variable-speed operation, it is essential to supply the synchronous motor with a variable frequency. This is done using a static converter, typically a DC-AC converter, as illustrated in **Figure V.6**.

The input source can be either a current source or a voltage source. At the output of the converter, both the amplitude of the stator voltage (in the case of voltage supply) or the amplitude of the stator current (in the case of current supply) and the frequency *f* are controlled. This arrangement allows for flexible speed control by adjusting the frequency and amplitude of the stator input, enabling efficient operation across different speed ranges.

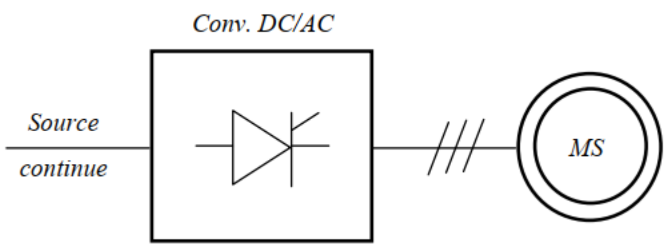


Figure.V. 6 : Synchronous Motor Powered by a DC/AC Converter

V.6.1 Self-Piloted Synchronous Motor :

In a self-piloted synchronous motor, the stator field rotates at a speed determined by the supply frequency, and the rotor field (excitation or magnets) in standard operation is "locked" to the stator field. When torque demand on the rotor increases, the two fields shift relative to each other. However, the dynamics of the stator and rotor fields are very different:

- ✓ The stator field dynamics, driven by the electrical time constants of the variable frequency source, are faster.
- ✓ The rotor field dynamics are slower due to the mechanical properties (inertia) of the rotating parts.

Thus, the stator field's dynamics are faster than the rotor field's. A sudden change in the supply frequency will cause the stator field to change its speed rapidly, while the rotor field cannot follow as quickly due to the inertia of the rotating components. This results in a significant shift between the two fields, potentially causing the machine to lose synchronism (or "decelerate").

Because of this, open-loop frequency variable operation carries a high risk of instability.

To address this problem, the key idea is to control the position of the rotor field relative to the stator field by imposing the angular shift between the two fields. This mode of operation is called "self-piloting" . The angular displacement between the rotor and stator fields is controlled to maintain synchronization.

Based on the torque expressions, there are two methods of self-piloting:

1. **Current and ψ Angle Regulation:** This method involves controlling the current I and the angle ψ, with the machine operating alongside a current-controlled inverter.
2. **Voltage and Internal Angle δ Control**: This method uses voltage control and the internal angle δ, with the self-piloted synchronous motor powered by a voltage-controlled inverter.

Requirements for Self-Piloted Operation:

- **Position Sensor**: A sensor is needed to detect the rotor position accurately.
- **Variable Frequency Power Source**: The motor is powered by either a current inverter or a voltage inverter that provides a variable frequency output.

Note

Open-loop operation of synchronous motors is used in limited applications where there are no sudden changes in speed or the torque of the driven loads.

V.6.1.1 Self-Piloted Synchronous Motor Powered by a Current Inverter

In this case, the synchronous motor is powered by a current inverter, and the control is based on the torque expression:: $T_{em} = 3p\phi_f I\ cos\psi$.

To control the torque of the machine, the focus is on adjusting the angle ψ and the amplitude of the current *I* (where the flux ϕ_f is typically kept constant).

The static converter associated with the machine must therefore enforce the current in each phase. To control the angle ψ, a rotor position sensor is required. This position sensor not only helps in controlling the angle but also provides the command signals for the converter that powers the machine, ensuring that:$\omega_s = p\ \Omega_s$.

the most common system setup is depicted in **Figure V.7**, where the self-piloted synchronous motor is paired with a current inverter. This configuration enables precise control of the motor by monitoring and adjusting both the current and the angular position of the rotor. This system allows for efficient torque control and stable operation in various speed ranges.

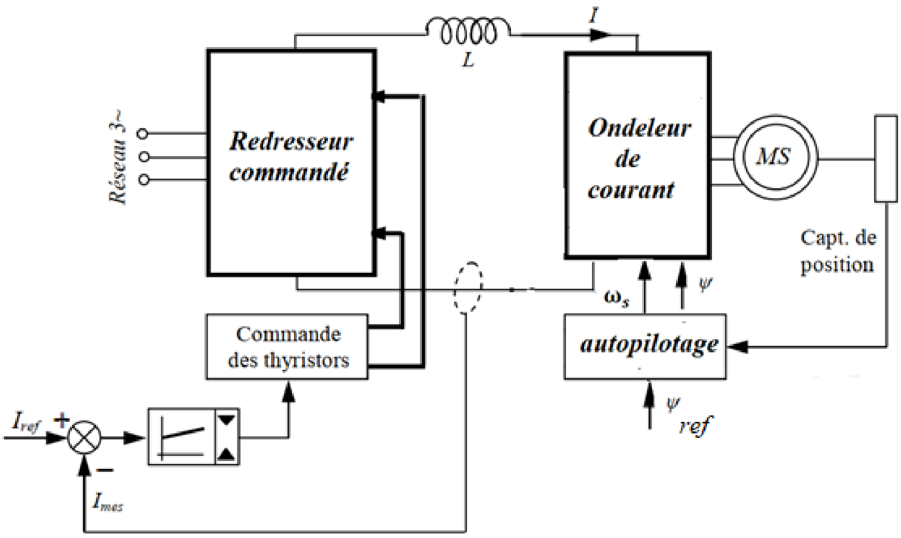


Figure.V. 7 : The self-piloted synchronous motor is paired with a current inverter

Advantages of the Self-Piloted Synchronous Motor Powered by a Current Inverter:

1. **Precise Torque Control**: By controlling the current amplitude and the angle ψ\, this method provides accurate and stable torque control, making it well-suited for applications where torque precision is crucial.
2. **Constant Flux Operation**: Since the flux ϕ_f is kept constant, the system operates efficiently across different load conditions, ensuring reliable performance.
3. **High Efficiency**: The use of a current inverter allows the system to maintain a high efficiency, especially under varying speed and load conditions.
4. **Good Dynamic Response**: The system can quickly respond to changes in load or speed demand, making it suitable for applications where rapid torque adjustments are necessary.
5. **Reduced Torque Pulsation**: This method helps in minimizing torque ripple, resulting in smoother operation, which is essential for precision applications.
6. **Capability of Regenerative Braking**: The current inverter can allow regenerative braking, where the motor can recover energy and feed it back to the grid during deceleration, improving energy efficiency.
7. **Suitability for High-Power Applications**: This method is often used in high-power applications such as industrial drives and large machinery due to its robustness and efficiency.

Disadvantages of the Self-Piloted Synchronous Motor Powered by a Current Inverter:

1. **Complex Control System**: The need for precise control of the angle ψ\psiψ and the current requires sophisticated control algorithms and hardware, which increases system complexity.
2. **Requirement of a Rotor Position Sensor**: A position sensor is necessary to monitor the rotor's position, adding to the system's cost and complexity. Failures or inaccuracies in the sensor can lead to performance issues.
3. **Harmonic Distortion**: The current inverter can introduce harmonics into the system, which may require additional filtering to avoid interference with other electrical equipment.
4. **Potential Instability**: Without proper control and tuning, the system can become unstable, especially in scenarios where the load changes suddenly or operates at low speeds.
5. **Expensive Components**: The overall cost of the system is higher due to the need for precise inverters, sensors, and control electronics, which can make it less economically viable for small-scale applications.
6. **Dependency on Inverter Performance**: The system's performance is highly dependent on the quality and capabilities of the inverter, meaning any inefficiencies or failures in the inverter can affect the motor's operation.
7. **Cooling Requirements**: The system may generate more heat due to the continuous high currents, leading to the need for advanced cooling solutions, which can increase operational costs.

V.6.1.2 Synchronous Motor Self-Piloted by a Voltage Inverter:

The principle of controlling the torque of a synchronous machine is based on the relationship between the internal phase shift angle δ, the supply voltage, and the stator pulsation ωs. These variables allow for control of the motor's performance in voltage-fed systems (eq V.18).

In voltage-controlled synchronous motors, torque control is primarily adjusted through:

1. **Internal Phase Shift Angle δ**: This angle represents the phase difference between the rotor's magnetic field and the stator's magnetic field. By adjusting δ, the motor's torque is controlled.

2. **Supply Voltage**: The voltage supplied to the motor determines the magnitude of the magnetic field in the stator, influencing torque and speed.
3. **Stator Pulsation ω_s** : This is related to the frequency of the supply voltage. The motor's speed is directly proportional to this frequency.

For operation at constant flux and nominal conditions, the ratio $\frac{V}{\omega_s}$ is kept constant, known as **scalar control**. This approach ensures stable operation of the motor by maintaining a fixed voltage-to-frequency ratio.

Key Components of Control:

- **Phase Shifter**: This device adjusts the internal angle δ for controlling the torque.
- **Rotor Position Detection System**: A sensor or encoder is used to monitor the rotor's position, ensuring precise control of the motor's torque and speed.

The scalar control method is particularly effective for applications requiring smooth speed control and constant flux operation.

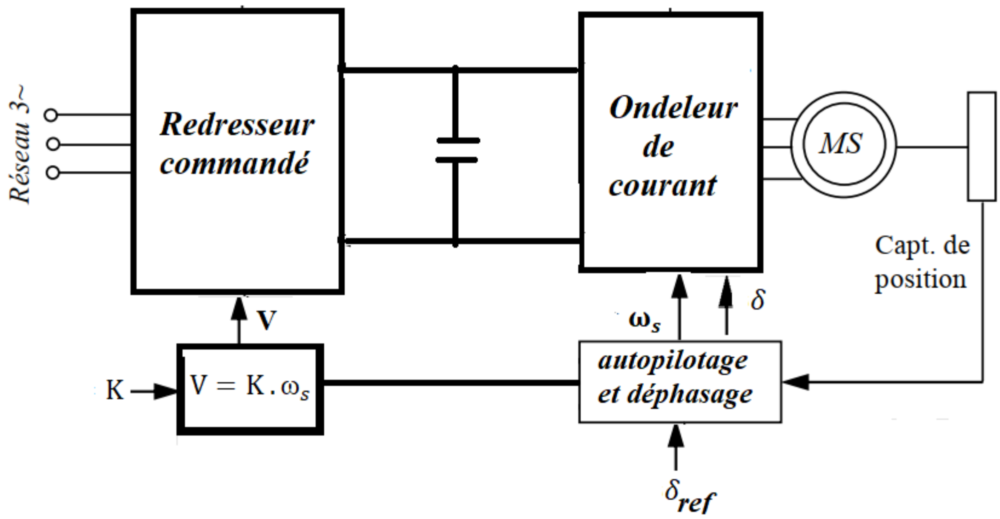


Figure.V. 8 : Commande scalaire d'une machine synchrone autopilotée

Advantages of Voltage Inverter-Controlled Self-Piloted Synchronous Motors:

1. **Precise Torque and Speed Control**: By adjusting the internal phase angle δ, supply voltage, and stator frequency, the motor offers accurate control of both torque and speed, making it suitable for high-performance applications.

2. **Wide Speed Range**: The method allows for smooth and efficient operation over a wide range of speeds by varying the frequency and voltage, making it ideal for variable-speed drives.
3. **Constant Flux Operation**: Maintaining a constant $\frac{V}{\omega_s}$ ratio ensures that the motor operates at optimal efficiency, reducing power losses and maintaining performance stability.
4. **High Efficiency**: Voltage inverter control typically leads to lower losses due to the reduction in mechanical and electrical stresses, improving the overall efficiency of the motor.
5. **No Need for Mechanical Commutators**: This method eliminates the need for mechanical components like brushes or slip rings, reducing wear and tear, thus increasing reliability and reducing maintenance costs.
6. **Adaptability to Different Load Conditions**: The motor can handle varying load conditions without significant performance drops, thanks to the adjustable voltage and frequency controls.

Disadvantages of Voltage Inverter-Controlled Self-Piloted Synchronous Motors:

1. **Complex Control System**: The need for precise rotor position sensors and phase shift controls makes the system more complex and costly compared to simpler motor control methods.
2. **Harmonic Distortion**: Voltage inverters can introduce harmonic distortions into the system, potentially causing noise, vibrations, and additional losses in the motor and the power network.
3. **Cost**: The components required for this method, such as inverters, sensors, and advanced control systems, make the overall setup more expensive than traditional motor control methods.
4. **Dependence on Precise Sensing**: The system's performance heavily relies on accurate rotor position detection. Any sensor malfunction can lead to instability or loss of control.
5. **Limited Performance at Very Low Speeds**: At very low speeds, maintaining the desired voltage-to-frequency ratio can become challenging, and the motor may experience reduced performance or torque ripple.

V.6.1.3 Comparison between Self-Piloted Synchronous Motor Powered by a Current Inverter and Self-Piloted Synchronous Motor Powered by a Voltage Inverter

Feature	Self-Piloted Synchronous Motor Powered by a Current Inverter	Self-Piloted Synchronous Motor Powered by a Voltage Inverter
Control Variables	Current amplitude I, phase angle ψ, flux ϕf	Voltage amplitude V, internal phase angle δ, stator frequency ωs
Primary Control Method	Controls the torque by adjusting the current amplitude and phase angle.	Controls torque by adjusting the voltage and internal phase angle δ.
Dynamic Response	Slower response due to inertia, but stable for torque control.	Faster response, better for dynamic applications due to voltage control.
Torque Control	Good torque control with fine adjustment via the current and flux.	Accurate torque control, especially at higher speeds, due to voltage variation.
Efficiency	Can be less efficient at low currents and speeds, especially with current ripple	Generally more efficient due to lower losses and better voltage control at all speeds
Operational Complexity	Requires a more complex current control loop, typically using current sensors and phase control mechanisms.	Voltage-based control can be simpler and more intuitive but still requires precise control of V/ωs.
Suitability for Low Speed	Better control at low speeds due to current-based regulation, but may experience torque ripple	Can struggle with maintaining performance at very low speeds due to challenges in maintaining V/ωs ratio
Harmonic Distortion	Higher harmonics due to current chopping, which can lead to noise and vibration.	Harmonics can also be present, but voltage control tends to produce fewer harmonic issues.

System Complexity and Cost	Typically more complex due to the need for current sensors, more sophisticated current controllers, and converters.	Simpler in comparison, but still requires sophisticated voltage control systems and position feedback.
Sensor Requirements	Requires accurate rotor position sensing to adjust current phase angle ψ.	Requires rotor position sensors to manage phase angle δ and voltage control.
Power Supply Type	Typically requires a constant DC current source for the inverter.	Uses a variable DC voltage source for the inverter.
Best Application Type	Better suited for applications requiring high torque at low speeds or stable current control.	Ideal for high-speed applications where rapid voltage adjustments improve performance.
Power Factor Control	Power factor can be controlled by adjusting the current and flux.	Power factor can be managed by adjusting the internal phase angle δ.
Motor Heating	Higher current levels can lead to more heat generation, especially at low speeds.	Lower heat generation due to better efficiency in voltage control, especially at nominal speeds.
Maintenance and Durability	Can have higher maintenance costs due to the complexity of current sensors and control systems.	Lower maintenance as the voltage-based system is simpler, with fewer active current components.

- **Current Inverter-Controlled Synchronous Motors**: These are more suitable for applications where fine torque control at low speeds is crucial, but they can be more complex and less efficient at higher speeds. They excel in handling high-torque situations.
- **Voltage Inverter-Controlled Synchronous Motors**: These motors are ideal for high-speed applications requiring precise control, lower harmonic distortions, and better efficiency. However, they may face challenges in very low-speed applications where maintaining a constant V/ωs is harder.

Each method has specific strengths depending on the speed, load, and complexity of the application

Bibliography

M H Rashid, « Power electronics. Circuit, devices and applications», Prentice Hall,New Jersey.

N Adjissi - 2023 - doctoral thesis. University of setif. « Diagnostic et observation des systèmes dynamiques hybrides: Association convertisseur multicellulaire-machine électrique».

L CHAABI - 2021 - doctoral thesis. University of guelma. «Conception d'un système expert pour le diagnostic des roulements dans les machines tournantes fonctionnant en régime variable».

R Takarli, A Amini, M Khajueezadeh, MS Zarbil- IEEE , 2023 . «A Comprehensive Review on Flywheel Energy Storage Systems: Survey on Electrical Machines, Power Electronics Converters, and Control Systems»

J Shair, H Li, J Hu, X Xie - Renewable and Sustainable Energy Reviews, 2021 - Elsevier. «Power system stability issues, classifications and research prospects in the context of high-penetration of renewables and power electronics».

Z Said, LS Sundar, AK Tiwari, HM Ali - Physics Reports, 2022 - Elsevier. «Recent advances on the fundamental physical phenomena behind stability, dynamic motion, thermophysical properties, heat transport, applications, and challenges of nanofluids»

N Hatziargyriou, J Milanovic - IEEE Transactions on Power Systems, 2020 . «Definition and classification of power system stability–revisited & extended ».

W Cao, Y Ma, F Wang, LM Tolbert - IEEE Transactions on Smart Grid, 2020. «Low-frequency stability analysis of inverter-based islanded multiple-bus AC microgrids based on terminal characteristics».

D. Grahame Holmes, Thomas A. Lipo ·Book, Wiley, 2003. «Pulse Width Modulation for Power Converters: Principles and Practice».

N Kularatna, Book, END, 1998, «Power Electronics Design Handbook: Low-Power Components and Applications ».

S Ishwar, Book, 2024, Pencil. «Control Schemes for DC Motors in Electric Drives».

S K Bhattacharya, Book, New age, 2003. «Control Of Electrical Machines».

J Pyrhonen, V Hrabovcova, R. Scott Semken, Book , Wiley, 2016. «Electrical Machine Drives Control».

R M Llorente, Book, 2020. «Practical Control of Electric Machines,Model-based Design and Simulation».

R Husson, Book, Wiley, 2013. «Control Methods for Electrical Machines».

H Bandar, Book, GRIN Verlag, 2023. «Speed Control of a DC Shunt Motor».

M Jibril, Book, GRIN Verlag, 2020. «DC Motor Speed Control with the Precence of Input Disturbance Using Neural Network Based Model Reference and Predictive Controllers».

M M Bundele, R Nair, Proceedings of ICRAE, 2023. «Recent Advances in Engineering ».

M A Husain, Book, BookRix, 2018. «DC Motor Control - A Case Study Four Quadrant Dc Motor Speed Control With Microcontroller».

N Mohan, S Raju, Book, Wiley, 2023. «Power Electronics, A First Course: Simulations and Laboratory Implementations».

A A. Zaki Diab, A-Hashima , M. Al-Sayed, H Hefnawy , Book, Springer Briefs in Electrical and Computer Engineering , 2020. «Development of Adaptive Speed Observers for Induction Machine System Stabilization».

M Wenzhong, B Lianping Bai , Book, Wiley, 2018. «Energy-saving Principles and Technologies for Induction Motorsbooks».

A El-Shahat, Book, BOD, 2023. « Induction Motors - Recent Advances, New Perspectives and Applications».

P Cochran, Book, Marcel Dekker INC, 2018. «Polyphase Induction Motors, Analysis: Design, and Applicationbooks ».

I Boldea, Syed A, Book, CRP press, 2010. «The Induction Machine Handbookbooks ».

M Wenzhong, B Lianping , Book, Wiley, 2018. «Energy-saving Principles and Technologies for Induction Motorsbooks».

Bs In E E A M Dudley, Book, Creative Media Partners LLC, 2023. «Connecting Induction Motorsbooks».

M T Lamchich , Book, InTech, 2011. «Torque Controlbooks ».

M Pustovetov, K Shukhmin, S Goolak , Book, Bentham Books, 2023. «Induction Motor Computer Models in Three-Phase Stator: A Technical Handbook ».

J Desai, Book, GRIN, 2022. « Speed Control of Interior Permanent Magnet Synchronous »

S-A. E-M ARDJOUN. Educational Course Support, University of Djillali Liabes De Sidi-Bel-Abbes, 2020. « Commande des systèmes électro-énergétique ».

N Zerzouri , Educational Course Support, University of Badji Mokhtar Annaba, 2022. « Entrainements Electriques ».

S Belkacem , Educational Course Support, University of Batna 2, , 2020. « Entrainements Electriques ».

A Seghiour , Educational Course Support, Higher School of Electrical Engineering and Energy of Oran, 2022. « Commande électrique».

K Ghlam, Educational Course Support, University of Telemcen, 2021. «Commande électrique des mécanismes industriels».

T LUBIN, Educational Course Support, University of Lorraine, 2022. «Commande des machines électriques ».

M. Vygodski, Book, The Mitr, 2023. «Cours De Commande Électrique ».

Y A Zorgani, H Zayani, Educational Course Support, Higher Institute of Technological Studies in Sfax**,** 2014 **. «** Commande Electrique des Machines **»** .

P C. Krause, T C. Krause , Book , wiley, 2022. **«** Introduction to Modern Analysis of Electric Machines and Drivesbooks **»** .

, **S. K. Sahdev,Book,** Cambridge University Press, 2018. **«** Electrical Machines**»** .

L. BAGHLI, Lecture Notes**,** IUFM d Lorraine – UHP, 2004 « Modélisation et Commande de la Machine Asynchrone »,

Nyachulue Njita, Bachelor’s Thesis, Helsinki Metropolia University of Applied Sciences, 2015 « 3-Phase PM Synchronous Motor, High Speed with Low Torque »

Jian Zhao,Yangwei Yu, MPS Proprietary Information. Patent Protected. Unauthorized Photocopy and Duplication Prohibited.« Brushless DC Motor Fundamentals, Application Note ».