Power Electronics Control of Electrical Drives

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Sciro International publishers

Title: Power Electronics control of Electrical Drives
Edition: First

Year: April 2025
ISBN: 978-93-342-7516-2

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Foreword

The convergence of power electronics and electrical drives has revolutionized countless industrial and transportation applications, ushering in an era of enhanced efficiency, precision, and control. From the delicate movements of robotic arms to the robust power delivery of electric vehicles, the seamless integration of these two fields underpins much of modern technological advancement. The ability to manipulate electrical energy with ever-increasing sophistication and apply it effectively to motor control is a cornerstone of sustainable and intelligent systems.

In this context, a comprehensive and insightful exploration of "Power Electronics Control of Electrical Drives" is both timely and essential. This book embarks on a journey through the fundamental principles, advanced techniques, and practical considerations involved in designing, implementing, and optimizing modern drive systems. It delves into the intricacies of power semiconductor devices, the architecture of various power converter topologies, and the sophisticated control algorithms that govern the behavior of electric motors.

The reader will find within these pages a structured and thorough treatment of key topics, ranging from the basic characteristics of different motor types to the nuances of pulse-width modulation strategies, vector control, and field-oriented control. Furthermore, the book likely addresses the crucial aspects of system design, including thermal management, protection circuits, and the impact of drive systems on power quality.

This book serves as a valuable resource for a diverse audience. For undergraduate and postgraduate students, it offers a rigorous foundation in the subject, equipping them with the theoretical knowledge and analytical tools necessary to excel in this dynamic field. Practicing engineers will find it to be a comprehensive reference, providing practical insights and advanced methodologies for tackling real-world challenges in drive system design and implementation. Researchers will appreciate the in-depth treatment of cutting-edge control strategies and emerging trends.

The importance of this subject cannot be overstated. As the world increasingly focuses on energy efficiency and electrification, the demand for skilled professionals who can design, analyze, and implement sophisticated power electronic control systems for electrical drives will only continue to grow. This book, therefore, stands as a significant contribution to the field, bridging the gap between theoretical understanding and practical application.

The book "Power Electronics Control of Electrical Drives" will serve as an indispensable guide for students, engineers, and researchers alike, empowering them to contribute to the ongoing advancements in this vital and ever-evolving domain.

-Authors

Dedicated to

Our respective
Parents, Spouse and Children

&

Sri.K.krishna Rao

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Control of DC Motors Through Phase controlled Rectifier

1.1. Introduction

Electrical drives are electromechanical systems that convert electrical energy into mechanical energy to control the motion of various machines and mechanisms. They are essentially a combination of an electric motor, a power electronic converter, a control unit, and a sensing unit, all working together to precisely regulate the motor's speed, torque, and position.

1.1.1. Components of an Electrical Drive System:

- **Electric Motor:** The primary component that converts electrical energy into mechanical energy. Common types include DC motors (shunt, series, compound), AC motors (induction, synchronous), stepper motors, and brushless DC motors.
- **Power Electronic Converter (Power Modulator):** This unit regulates the power flow from the source to the motor, enabling the motor to achieve the required torque-speed characteristics. It also controls source and motor currents within permissible limits during transient operations (starting, braking, speed reversal) and converts the input electrical energy into the form required by the motor (e.g., AC to DC, DC to AC, or

adjusting voltage/frequency). Examples include rectifiers, choppers, inverters, and AC voltage controllers.

- **Control Unit:** This is the "brain" of the drive, controlling the power modulator based on input signals and feedback from the sensing unit. Modern control units often utilize microprocessors for sophisticated control, including features like interlocking, sequencing, and fault protection.
- **Sensing Unit:** This unit provides feedback about the motor's operating parameters, such as speed (using tachometers or encoders) and current (using current sensors). This feedback is crucial for closed-loop control to ensure accurate and stable operation.

1.1.2. Control of Electrical Drives:

The control of electrical drives typically involves adjusting the voltage, current, and/or frequency supplied to the motor to achieve the desired output characteristics. This can be broadly classified into:

- **Speed Control:**
  - **DC Drives:** Achieved through armature voltage control, field flux control, or a combination of both. Power electronic converters like controlled rectifiers and DC choppers are used for precise control.
  - **AC Drives:** Achieved through stator voltage control, rotor voltage control (for slip-ring motors), or, most commonly, variable voltage and frequency (V/f) control using inverters. The V/f control maintains a constant air gap flux, ensuring stable operation over a wide speed range.
  - **Closed-loop Speed Control:** A widely used method that employs an inner current control loop within an outer speed loop. A sensor (e.g., tachometer) measures the actual speed, which is then compared to a reference speed. The error signal is processed by a controller (e.g., PID controller) to adjust the power converter output and correct the speed.

- **Torque Control:** Directly controlling the motor's torque, often used in applications like battery-operated vehicles and electric trains where the driver sets a torque reference.
- **Position Control:** For applications requiring precise positioning, such as robotics and machine tools, the drive system incorporates position feedback (e.g., using encoders) to ensure the motor reaches and holds a specific position.

1.1.3. Applications of Electrical Drives:

Electrical drives are ubiquitous, found in almost every sector due to their versatility and control capabilities.

- **Industrial Applications:**
    - **Manufacturing:** Machine tools (lathes, milling, grinding machines), presses, punches, rolling mills, textile mills, paper mills, cement mills.
    - **Material Handling:** Conveyors, cranes, hoists, lifts, storage/retrieval systems.
    - **Fluid Handling:** Pumps, fans, compressors (e.g., in refrigeration and air conditioning).
    - **Robotics:** For precise speed and position control.
- **Transportation:**
    - Electric trains, locomotives, electric vehicles.
    - Ship propulsion.
- **Domestic Applications:**
    - Washing machines, mixers, electric razors, escalators, gate drives.
- **Specialized Applications:**
    - High-frequency spindles for internal grinding.
    - Petrochemical industries (for fluid handling with flow control).

1.1.4. Advantages of Electrical Drives:

- **Flexible Control Characteristics:** Offer wide and smooth control over speed, torque, and position, allowing for precise operation.
- **High Efficiency:** Electrical energy conversion to mechanical energy is highly efficient, leading to lower operating costs.
- **Wide Operating Range:** Available in a wide range of power (milliwatts to megawatts), speed, and torque.
- **Clean Operation:** No fuel combustion, hence no flue gases, smoke, or pollution.
- **Less Maintenance:** Compared to mechanical or other prime mover drives, electrical drives generally require less maintenance.
- **Compact Size:** Being compact, they require less space for installation.
- **Economical:** Lower running costs due to high efficiency and lower maintenance.
- **Reliability:** Generally reliable and have a comparatively longer lifespan.
- **Ease of Operation:** Can be easily started, stopped, reversed, and even remotely controlled.
- **Quick Response:** Offer fast response to changes in control signals.
- **Electric Braking:** Superior and economical braking systems are possible.
- **No Fuel Storage/Transportation:** Eliminates the need for fuel storage and transportation.
- **Easy Power Transmission:** Electrical energy can be easily transmitted over long distances through transmission lines.

1.1.5. Disadvantages of Electrical Drives:

- **Reliance on Electrical Supply:** Cannot operate in the event of an electrical power supply failure.
- **Limited Portability:** Not suitable for applications in remote areas where an electrical power supply is unavailable.
- **Initial Cost:** The initial investment for power electronic converters and sophisticated control systems can be higher than simpler mechanical

drives, especially for variable speed applications.

- **Harmonic Distortion:** Power electronic converters can introduce harmonic distortions into the power supply system, which may require additional filtering.
- **Complexity:** Modern electrical drives with advanced control systems can be complex to design, install, and troubleshoot.
- **Sensitivity to Environment:** Electronic components can be sensitive to extreme temperatures, humidity, and dust, requiring suitable enclosures and environmental control.
- **Electromagnetic Interference (EMI):** Switching devices in drives can generate EMI, which might interfere with other electronic equipment if not properly mitigated.

Despite these disadvantages, the numerous advantages and increasing demand for precise, efficient, and automated control have made electrical drives indispensable in almost all industrial and domestic applications.

1.2. Electrical Drive System

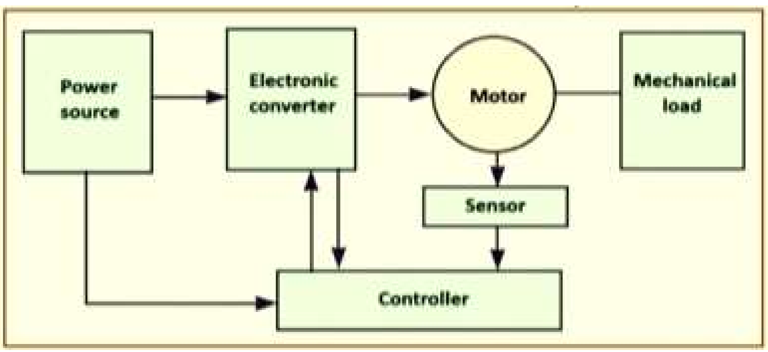


Figure 6-1. Functional blocks of the electrical drive system

A modern electrical drive system has six main functional blocks (Fig 1). These are a mechanical load, a motor, a converter, a power source, a sensor, and a controller. The power source provides the energy the drive system needs. The main function of a converter is to transform the wave-form of a power source to that needed by the electric motor in order to achieve the desired performance. Majority of the converters provide adjustable voltage, current, and / or frequency to control the speed. The converter interfaces the motor with adjustable voltage, current, and / or frequency. The controller supervises the operation of the entire system to improve overall system performance and stability.

The diagram which shows the basic circuit design and components of a drive, also shows that, drives have some fixed parts such as, load, motor, power processor, control unit, and source. These equipment's are termed as parts of drive system. Power processor is an electronic converter which controls the power flow to motor to get variable speed. It performs several functions such as (i) it processes flow of power from the source to the motor and impart speed–torque characteristics needed by the load, (ii) it regulates source and motor currents within permissible values, such as starting, braking, and speed reversal conditions, (iii) it selects the mode of operation of motor, i.e., motoring or braking, and (iv) It converts source energy in the form suitable to the motor.

Control unit controls the function of power processor. The nature of control unit for a particular drive depends on the type of power processor used. When semi-conductor converters are used, the control unit consists of firing circuits. Micro-processors are also used when sophisticated control is needed. Sensing unit consists of speed sensor or current sensor. The sensing of speed is needed for the implementation of closed loop speed control schemes. Speed is normally sensed using tachometers coupled to the motor shaft. Current sensing is needed for the implementation of current limit control.

AC-DC, AC-AC, DC-AC and DC-DC converters are some electronic converters used in drives. In AC-DC converter (Fig 2a), the AC wave form is converted to DC with adjustable magnitude. The input can be a single or multi-phase source. This type of converter is used in DC drives. In AC-AC converter (Fig 2b), the input wave-form is typically AC with fixed magnitude and frequency. The output is an AC with variable frequency, magnitude or both. In DC-AC converter (Fig 2c), the DC wave-form of the power source is converted to a single-phase, or multi-phase AC wave-form. The output frequency, current, and / or voltage can be adjusted as per the application. This type of converter is suitable for AC motors. The DC-DC converter (Fig 2d) is also known as 'chopper'. This converter is used to convert the constant input DC wave form to a DC wave-form with variable magnitude. The typical application of this converter is in DC motor drives.

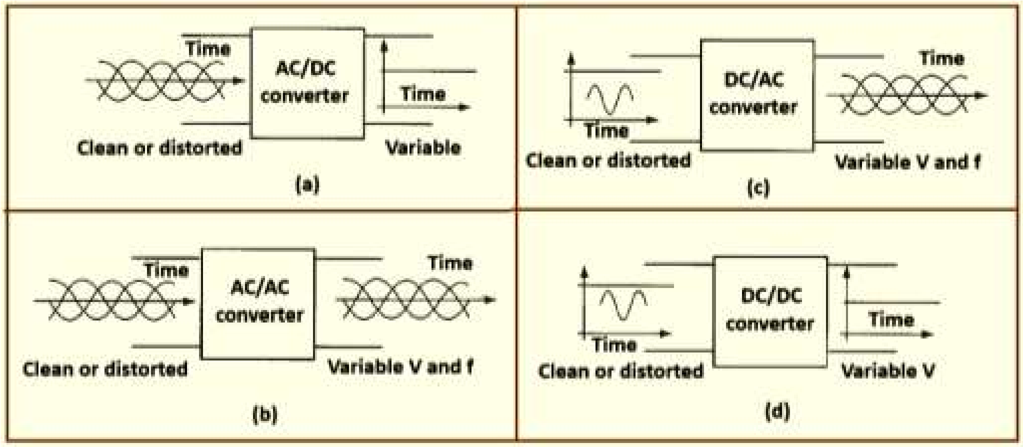


Figure 6-2. Types of converters

Sensor senses the speed of motor and sends signal to controller. A well design controller has several functions. The most basic function is to monitor system variables, compare with some desired values, and then readjust the converter output until the system achieves a desired performance. This feature is used in such applications as speed or position control. In case of rectifier converters, the rectifier converts the utility supply voltage to a DC voltage with a fixed or adjustable magnitude. The normally used rectifier topologies include multi-pulse diode rectifiers, thyristor rectifiers, and pulse-width modulated (PWM) rectifiers. Controller controls the power output of power processor. The power processor sends controlled output voltage to motor. Micro-controller and micro-processor are the normally used controllers.

For the design of the electrical drive system, several other things including the electric motor is to be considered. While designing the electrical drive system, the same system performance can be achieved in different ways. The final criterion for the best design is not only the economic reasons such as initial investment, and running cost etc., but also non-economic reasons such as environmental friendliness, ethics, and regulations. Recently, because of the concern of engineering to the social responsibility, the non-economic reasons have gained importance.

The thyristor DC drive remains an important speed-controlled industrial drive, especially where the higher maintenance cost associated with the DC motor brushes is tolerable. The controlled (thyristor) rectifier provides a low-impedance adjustable DC voltage for the motor armature, thereby providing speed control.

Until the 1960s, the only really satisfactory way of obtaining the variable-voltage DC supply needed for speed control of an industrial DC motor was to generate it with a DC generator. The generator was driven at fixed speed by an induction motor, and the field of the generator was varied in order to vary the generated voltage. The motor / generator (MG) set could be sited remote from the DC motor, and multi-drive sites (e.g., rolling mill in a steel plant) had large rooms full of MG sets, one for each variable-speed motor installed in the rolling mill. Three machines (all of the same power rating) were needed for each of these 'Ward Leonard' drives. For a brief period in the 1950s they were superseded by grid-controlled mercury arc rectifiers, but these were soon replaced by thyristor converters which offered cheaper first cost, higher efficiency (typically over 95 %), smaller size, reduced maintenance, and faster response to the changes in set speed. The disadvantages of rectified supplies were (i) the wave-forms are not pure DC, (ii) the overload capacity of the converter is very limited, and (iii) a single converter is not capable of regeneration.

Though no longer pre-eminent, knowledge of the DC drive is valuable for several reasons namely (i) the structure and operation of the DC drive are reflected in almost all other drives, and lessons are learned from the knowledge of the DC drive, (ii) the DC drive tends to remain the yard-stick by which other drives are judged, and (iii) under constant-flux conditions the behavior is governed by a relatively simple set of linear equations, so predicting both steady-state and transient behavior is not difficult. In case of the successors of the DC drive, notably the induction motor drive, it is found that things are much more complex, and that in order to overcome the poor transient behavior, the strategies adopted are based on emulating the DC drive.

For motors up to a few kWs the armature converter can be supplied from either single-phase or three-phase mains, but for larger motors three-phase is always used. A separate thyristor or diode rectifier is used to supply the field of the motor, the power is much less than the armature power, so the supply is frequently single-phase. The arrangement is typical of the majority of the DC drives and provides for closed-loop speed control.

The main power circuit consists of a six-thyristor bridge circuit, which rectifies the incoming AC supply to produce a DC supply to the motor armature. The assembly of thyristors, mounted on a heat-sink, is normally referred to as the 'stack'. By altering the firing angle of the thyristors, the mean value of the rectified voltage can be varied, thereby allowing the motor speed to be controlled. The controlled rectifier produces a crude form of DC with a pronounced ripple in the output voltage. This ripple component gives rise to pulsating currents and fluxes in the motor, and in order to avoid excessive eddy-current losses and commutation problems, the poles and frame are to be of laminated construction. It is accepted practice for motors supplied for use with thyristor drives to have laminated construction, but older motors frequently have solid poles and / or frames, and these do not always work satisfactorily with a rectifier supply. It is also the norm for drive motors to be supplied with an attached 'blower' motor as standard. This provides continuous through ventilation and allows the motor to operate continuously at full torque even down to the lowest speeds without overheating.

Low power control circuits are used for monitoring the principal variables of interest (normally motor current and speed), and for generating appropriate firing pulses so that the motor maintains constant speed despite variations in the load. The 'speed reference' is typically an analog voltage varying from 0 V to 10 V, and achieved from a manual speed-setting potentiometer or from elsewhere in the plant. The combination of power, control, and protective circuits constitutes the converter. Standard modular converters are available as off-the-shelf items in sizes from 0.5 kW up to several hundred kW, while larger drives are to be tailored to individual needs. Individual converters can be mounted in enclosures with isolators, and fuses etc., or groups of converters can be mounted together to form a multi-motor drive.

By no stretch of imagination, the wave-forms of armature voltage can be thought of as good DC, and it is not unreasonable to question the wisdom of feeding such an unpleasant looking waveform to a DC motor. In fact, it turns out that the motor works almost as well as it works if fed with pure DC, for two main reasons. Firstly, the armature inductance of the motor causes the wave-form of armature current to be much smoother than the wave-form of armature voltage, which in turn means that the torque ripple is much less than might have been feared, and secondly, the inertia of the armature is sufficiently large for the speed to remain almost steady despite the torque ripple. It is indeed fortunate that such a simple arrangement works so well, since any attempt to smooth-out the voltage waveform (perhaps by adding smoothing capacitors) proves to be prohibitively expensive in the power ranges of interest.

The ripple voltage causes a ripple current to flow in the armature, but because of the armature inductance, the amplitude of the ripple current is small. In other words, the armature presents a high impedance to AC voltages. Because of the smoothing effect of the armature inductance, the current ripple is relatively small in comparison with the corresponding voltage ripple. The average value of the ripple current is of course zero, so it has no effect on the average torque of the motor. There is however a variation in torque every half-cycle of the mains, but since it is of small amplitude and high frequency the variation in speed (and hence back emf) is not normally noticeable. The current at the end of each pulse is the same as at the beginning, so it follows that the average voltage across the armature inductance is zero. Hence, the average applied voltage can be equated to the sum of the back emf (electromotive force), which is exactly the same as for operation from a pure DC supply. This is very important, since it underlines the fact that the mean motor voltage can be controlled, and hence the speed, simply by varying the converter delay angle.

The smoothing effect of the armature inductance is important in achieving successful motor operation. The armature acts as a low-pass filter, blocking most of the ripple, and leading to a more or less constant armature current. For the smoothing to be effective, the armature time-constant needs to be long compared with the pulse duration (half a cycle with a 2-pulse drive, but only one sixth of a cycle in a 6-pulse drive). This condition is met in all 6-pulse drives, and in several 2-pulse drives. Overall, the motor then behaves much as it is if it has been supplied from an ideal DC source.

Industrial electronics and electric drives technology have made considerable developments after several decades of the dynamic evolution of power semiconductor devices, converters, pulse width modulation (PWM) techniques, and advanced control and simulation techniques. Recently its applications have been fast expanding in the industry because of the reduction in cost and size and improvements in performance.

In the beginning of the 20th century, since the price of the electric motor and its associated control system was very expensive, a large electric motor was used in the whole plant, and the mechanical power from the motor was distributed to every mechanical equipment where the mechanical power is needed through gears and belts. Because of the reduction of the price of the electric motor and the control system, a separate electric motor is being used for each mechanical equipment, which has several motions, and still the mechanical power from the motor is transmitted and converted to an appropriate form at each point of the motion in the equipment.

Recently, even in a single mechanical equipment, multiple electric motors are used at each motion point. The motion needed at that point can be achieved by the motor directly without speed or torque conversion from the motor. In this way, the efficiency of the system can be improved. Also, the motion control performance can be improved by eliminating all non-linear effects and losses such as backlash, torsional oscillation, and friction. In the future, this tendency can be continued and the custom designed motor can be used widely at each moving part. For example, for high-speed operation, the high-speed motor can be used without amplification of the speed through gears. For linear motion, a linear motor can be used without a ball screw mechanism. For high-torque low-speed traction drive, the direct drive motor can be used for reducing the size and loss of the system.

The control method of the motor drive system has been developed from manual operation to automatic control system. Recently, intelligent control techniques have been used and the control system itself can operate the system at optimal operating conditions without human intervention. Also, in the early stages of automatic control of the motor drive system, the simple supervisory control has been implemented, and the control unit has transferred the operating command set by the user to the motor drive system. Through the direct digital control, right now, distributed intelligent control techniques are used widely in the up-to-date motion control system.

In the late 1950s, with the invention of the thyristor, power electronics has been introduced. The power semi-conductor has been the key of the power electronics. With the rapid improvement of performance against cost of the power semi-conductors, the power electronics technology has improved in a revolutionary way. The original thyristors of the 1950s and 1960s can only be turned on by an external signal to the gate but is to be turned off by the external circuits. And it needs a complicated forced commutating circuit. In the 1970s, the gate turn-off (GTO) thyristor has been commercialized. And the GTO thyristor can be not only turned on but also turned off by external signal to the gate of the semi-conductor. In the late 1970s, the bipolar power transistor opened a new horizon of the control of power because of its relatively simple on and off capabilities.

Traditional drives, which use asynchronous cage motors or DC motors, are unsuitable for sufficiently precise and energy-efficient control of motors in dynamic and static operating conditions. Because of the development of new, highly efficient and characterized with short response IGBT (insulated gate bi-polar transistors), a marked rise in the number of VSD systems can be observed in the recent years. High interest in industrial applications of the VSD systems is because of their advantages which include controlled starting current, reduced harmful disturbances in the power grid, lower power requirement of the drive at start-up, controlled value and characteristics of accelerations, smooth regulation of motor speed (measured in revolution per minute, rpm), controlled torque, fully controlled drive deceleration, electricity savings, power recuperation, easy motor reverse, and elimination of additional mechanical parts.

With the transistor, general-purpose VVVF (variable voltage variable frequency) inverters has been commercialized and are being used in several ASD applications. Recently, with the introduction of the integrated gate-controlled thyristor (IGCT) and the fifth-generation IGBT, the performance of the electric motor drive system has been dramatically improved in the sense of output power of the system and the control bandwidth of the motion of the drive system. However, still, all the power semi-conductors have been fabricated based on silicon, and its junction temperature has been limited up to 150 deg C in the majority of the cases. Recently, the power semi-conductor based on silicon carbide (SiC) has been introduced, and the operating temperature and operating voltage of the power semi-conductor can be increased several-fold. With this material, the semi-conductor operating at above 300 deg C and at several thousand-voltage can conduct several hundred amperes within one-tenth of the wafer size of the device made by silicon. In particular, the Schottky diode and field effect transistor (FET) based on SiC have been the first devices in the field, and extraordinary performances of the devices have been reported.

In the early days of research and development, the control signal for the power semi-conductors came from analog electronics circuits consisting of transistors, diodes, and 'R' (resistor), 'L' (inductor), 'C' (capacitor) passive components. With the development of electronics technology, especially integrated circuit technology, the mixed digital and analog circuit consisting of operational amplifiers and TTL (transistor-transistor logic) circuit has been used. Recently, except for high-frequency switching power supplies, the major part of the power electronics system, especially the electric motor drive system, is controlled digitally by one or a few digital signal processors (DSP).

In power-factor correction (PFC) converters, by applying semi-conductors such as IGBT, GTO, IGCT, a silicon-controlled rectifiers (SCR) allows to reduce harmonics and to improve power factor. Rectifiers of active front end (AFE) type can operate with high power factor or any active-reactive power combination. These rectifiers can be classified as voltage-source rectifiers (VSRs) and current-source rectifiers (CSRs). AFE drives are inherently 'four-quadrant' ones (i.e. they can drive and brake in both directions of rotation with any excess of kinetic energy during braking returned to the supply).

For meeting the motor-side challenges, a variety of inverter topologies can be adopted for the MV drive. The most used inverters are conventional two-level inverter, three-level neutral-point clamped (NPC) inverter, seven-level cascaded H-bridge inverter, and four-level flying-capacitor inverter. Either IGBT or IGCT can be employed in these inverters as switching devices. Current-source inverter (CSI) technology has been widely accepted in the drive industry. The most frequently used inverters are load-commutated inverter (LCI), pulse width modulation (PWM) CSI, and parallel PWM CSI.

The SCR-based LCI is particularly suitable for very large synchronous motor drives, while the PWM CSI is a preferred choice for most industrial applications. The parallel PWM CSI is composed of two or more single-bridge inverters connected in parallel for super-high-power applications. Symmetrical IGCTs are typically used in the PWM current source inverters. CSI technology is well suited for high-power drives. The current-source converters feature a simple converter structure, low switch count, low switching dV/dt, and reliable over-current / short-circuit protection. The main drawback lies in its limited dynamic performance because of the use of a large DC choke.

Traditional two-level voltage-source inverters (VSIs) (2L-VSIs) have been limited to low-power or medium-power applications because of the power semi-conductor voltage limits. Series connection of switching devices has enabled high power 2L-VSIs. The well-known 2L-VSI is also used in medium-power and high-power traction and industrial high-power drives. The 2L-VSI inverter is a simple converter topology and has an easy PWM modulation pattern. However, the inverter produces high dV/dt and high THD (total harmonic distortion) in its output voltage and, hence, frequently needs a large-size LC (inductor-capacitor) filter installed at its output terminals.

The three-level NPC-VSI (3L-VSI) has been successfully used in the industry in past years. The main features of the NPC (neutral point clamped) inverters include reduced dV/dt and low THD in its AC output voltages in comparison to the 2L-VSI topology. The 3L-VSI can be used in MV drives to reach a certain voltage level without switching devices in a series connection. Hence, the efficiency levels can reach 99 %. It is to be noted that, in terms of efficiency, the VSIs and CSIs are attractive for non-regenerative low dynamic requirement drives. For regenerative applications, the three-level NPC VSI achieves higher efficiency in comparison to the CSI converter. For very high-power applications, the thyristor-based current-source topology offers considerably higher performance because of the low-voltage drop of the semi-conductors used.

The primary adverse outcome of a VSD for a power system is the effect of harmonics generated by the VSD. There are two mechanisms by which the VSD generates harmonic currents. The first mechanism is the converter operation which injects harmonic currents into the supply system by an electronic switching process. The second mechanism is the inverter operation. The magnitude of the harmonics generated by the VSD is determined by (i) topology of the drive (number of pulses, and rectifier type), (ii) percentage of the total power system capacity which the VSD represents, (iii) stiffness or short circuit capacity of the power system supplying the VSD, (iv) whether or not the VSD is electrically isolated from other sources of harmonics, (v) installation practices for the VSD, and (vi) rating of electrical load of the VSD.

When planning the installation of VSDs in a power supply system, a choice has to be made between designing non-linear devices for low levels of wave-form distortion or installing harmonic compensation equipment at the terminals. The first solution is frequently possible by phase-shifting of the transformers and / or the control of converter bridges or by the use of switching devices with turn-off capability. Second solution of harmonic elimination is achieved by means of filters (external harmonic compensation). Passive filters comprise inductance, capacitance, and resistance elements configured and tuned to control harmonics characterizing operation of particular VSD system. These are normally used and are relatively inexpensive compared with other means for eliminating harmonic distortion. As these have disadvantage of potential adverse inter-action with the power system, it is important to verify all possible system inter-actions in the system planning and design stage.

The AC motor drive, as the name suggests, needs an AC input to the induction motor used to drive large industrial loads. An AC motor drive takes an AC energy source, rectifies it to a DC bus voltage and, implementing complex control algorithms, inverts the DC back to AC into the motor using complex control algorithms based on load demand.

The power converter topology used in the power stage is that of a three-phase inverter which transfers power in the range of kW to MW. Inverters convert DC power to AC power. Typical DC bus voltage levels are 600 V to 1,200 V. Considering the high power and voltage levels, the three-phase inverter uses six isolated gate drivers. Each phase uses a high-side and low-side insulated gate bi-polar transistor (IGBT) switch. Operating normally in the 20 kHz (kilohertz) to 30 kHz frequency range, each phase applies positive and negative high-voltage DC pulses to the motor windings in an alternating mode.

1.3. Introduction to Thyristor controlled Drive

Thyristor-controlled drives are widely used in industrial applications for controlling the speed and torque of DC and AC motors. They utilize thyristors, which are semiconductor devices, to regulate the voltage and current supplied to the motor, thereby achieving precise control over its operation.

What is a Thyristor? A thyristor, also known as a Silicon Controlled Rectifier (SCR), is a four-layer, three-junction semiconductor device that acts as a switch. It can rapidly switch large currents and voltages. Once triggered, it remains in the conducting state until the current falls below a certain level or is intentionally turned off.

How do Thyristor-Controlled Drives Work? In a thyristor-controlled drive, thyristors are arranged in a rectifier circuit (e.g., a full-wave bridge rectifier). By controlling the firing angle (the point at which the thyristor is triggered during each AC cycle), the average output voltage supplied to the motor can be varied.

- **For DC Motors:** Thyristor drives convert AC supply into variable DC voltage. By changing the firing angle, the DC voltage fed to the motor armature can be controlled, which in turn controls the motor's speed. For reversing the direction, additional circuitry or a dual converter arrangement is used.
- **For AC Motors (e.g., Induction Motors):** While less common for direct speed control of AC motors compared to VFDs (Variable Frequency Drives), thyristors can be used in some applications for soft starting, voltage control, and in cycloconverters for frequency conversion.

1.3.1. Key Features and Advantages:

- **Robustness:** Thyristor s are very robust and can handle high power.
- **High Efficiency:** They have low power dissipation when fully conducting.
- **Cost-Effective:** Often more economical for high-power applications compared to other power electronic converters.
- **Reliable:** Known for their reliability in industrial environments.

Here is an image illustrating a thyristor-controlled drive:

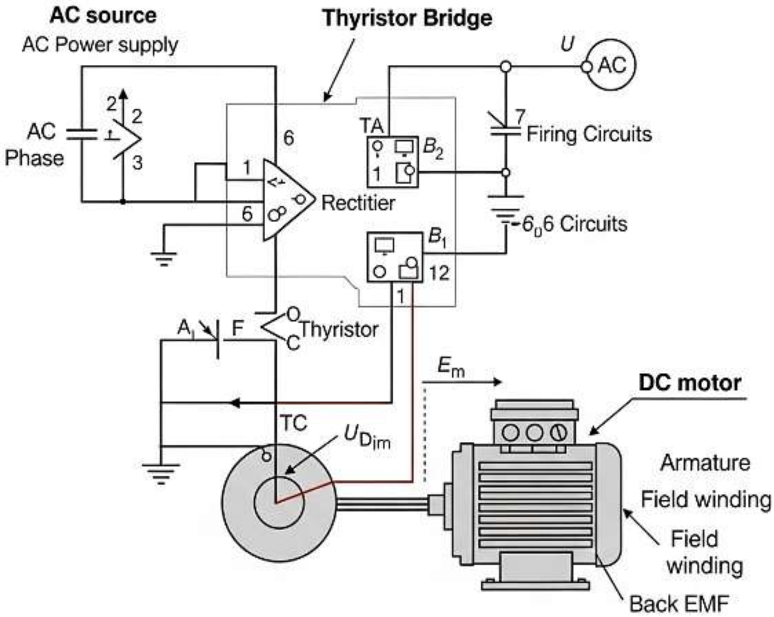


Figure 1-1. Thyristor Controlled Drive

Applications: Thyristor-controlled drives are commonly found in:

- Steel rolling mills
- Cranes and hoists
- Electric traction systems
- Paper mills
- Cement mills
- Textile industries

This image illustrates the basic components of a thyristor-controlled drive for a DC motor. It shows how the AC input is rectified by the thyristor bridge to provide a variable DC voltage to the motor.

1.4. Introduction to Electrical Drive

Motion control is required in large number of industrial and domestic applications. Systems employed for getting the required motion and their smooth control are called Drives. Drives require prime movers like Diesel or petrol engines, gas or steam turbines, hydraulic motors or electric motors. These prime movers deliver the required mechanical energy for getting the motion and its control. Drives employing Electric motors as prime movers for motion control are called *Electric Drives*.

1.4.1. Advantages of Electrical Drives:

- The steady state and dynamic performance can be easily shaped to get the desired load characteristics over a wide range of speeds and torques.
- Efficient Starting /Braking is possible with simple control gear.
- With the rapid development in the field of Power Electronics and availability of high speed/high power devices like SCRs, Power MOSFETs, IGBTs etc., design of Efficient Power Converters to feed power to the electric drives has become simple and easy.
- With the rapid development in the computer's HW & $SW, PLCs$ and Microcontrollers which can easily perform the control unit functions have become easily available.
- Electric motors have high efficiency, low losses, and considerable overloading capability. They have longer life, lower noise and lower maintenance requirements.
- They can operate in all the four quadrants of operation in the Torque/Speed plane. The resulting Electric braking capability gives smooth deceleration and hence gives longer life for the equipment. Similarly Regenerative braking results in considerable energy saving.

They are powered from electrical energy which can be easily transferred, stored and handled. Block diagram of an Electrical drive is shown in the figure 1.2.

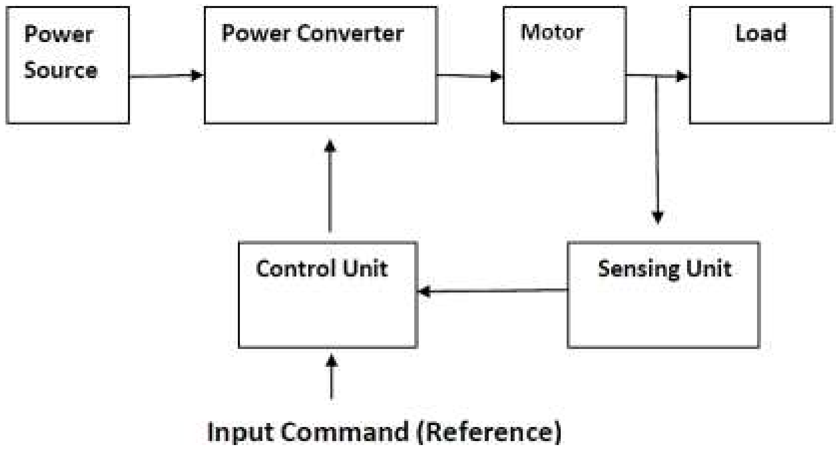


Figure 1-2. Block diagram of an Electrical drive

Parts of an Electric Drive: The different parts &their functions are explained here.

The load: Can be any one of the systems like pumps, machines etc. to carry out a specific task. Usually, the load requirements are specified in terms of its speed/torque demands. An electrical motor having the torque speed characteristics compatible to that of the load has to be chosen.

Power Converter: Performs one or more of the following functions.

- Converts Electrical energy from the source into a form suitable to the motor. Say AC to DC for a DC motor and DC to AC for an Induction motor.
- Controls the flow of power to the motor so as to get the Torque Speed characteristics as required by the load.
- During transient operations such as Starting, Braking, Speed reversal etc. limits the currents to permissible levels to avoid conditions such as Voltage dips, Overloads etc.
- Selects the mode of operation of the Motor i.e., Motoring or Braking

1.5. Power Converters:

a *power converter* is the central component that enables precise and efficient control over the electric motor. Essentially, it acts as an interface between the power source (like the utility grid or a battery) and the motor, transforming electrical energy from one form to another to meet the motor's specific operating requirements.

There are several types of power converters depending upon the type of motor used in a given drive. A brief outline of a few important types is given below.

1.5.1. Role of Power Converters in Electrical Drives:

The primary roles of power converters in electrical drives include:

- **Energy Conversion:** They convert the available electrical energy (e.g., fixed AC voltage and frequency from the grid, or DC from a battery) into the desired form (e.g., variable AC voltage and frequency for an AC motor, or variable DC voltage for a DC motor).
- **Speed Control:** By varying the voltage and/or frequency supplied to the motor, power converters allow for precise control of the motor's speed, from zero to above its rated speed.
- **Torque Control:** They enable control over the motor's torque, which is crucial for managing acceleration, deceleration, and load handling.
- **Direction Control:** Power converters can reverse the direction of rotation of the motor.
- **Power Flow Control:** They manage the flow of electrical energy between the source and the motor, allowing for efficient operation and, in some cases, regenerative braking (where energy is fed back to the source during deceleration).
- **Efficiency Improvement:** By optimizing the power supplied to the motor based on the load, power converters significantly improve energy efficiency, especially in applications with varying loads.

- **Soft Starting and Stopping:** They enable smooth acceleration and deceleration of the motor, reducing mechanical stress on the equipment and extending its lifespan.

1.5.2. Applications in Electrical Drives:

Power converters are indispensable in a vast array of electrical drive applications, including:

- **Industrial Automation:** Conveyor systems, pumps, fans, compressors, robotics, machine tools.
- **Transportation:** Electric vehicles (EVs), hybrid electric vehicles (HEVs), electric trains, trams, elevators.
- **Renewable Energy Systems:** Control of wind turbine generators and solar pump systems.
- **Household Appliances:** Washing machines, refrigerators (with variable speed compressors), air conditioners.
- **HVAC Systems:** Precise control of fans and blowers for energy efficiency.
- **Material Handling:** Cranes, hoists, forklifts.

1.5.3. Advantages of Using Power Converters in Electrical Drives:

The integration of power converters in electrical drives offers numerous benefits:

- **High Efficiency:** Modern power electronic converters, often utilizing semiconductor devices like MOSFETs, IGBTs, and thyristors, achieve very high efficiencies, minimizing energy waste.
- **Precise Control:** They provide fine-tuned control over motor speed, torque, and position, leading to improved process control and product quality.
- **Energy Savings:** By allowing motors to operate at optimal speeds and torques, especially under varying load conditions, significant energy savings can be achieved.

- **Reduced Mechanical Stress:** Soft starting and stopping capabilities extend the lifespan of mechanical components and reduce maintenance needs.
- **Flexibility:** They enable the use of highly efficient AC motors in applications that traditionally required DC motors due to simpler speed control.
- **Reduced Noise and Vibration:** Smoother operation of motors due to precise control.
- **Regenerative Braking:** The ability to return energy to the power source during braking, further enhancing efficiency in applications with frequent stops.

1.5.4. Types of Power Converters

- **AC to DC converters:** They convert single phase/Polyphase AC supply into fixed or variable DC supply using either simple rectifier circuits or controlled rectifiers with devices like thyristors, $IGBTs.Power\ MOSFETs$ etc. depending upon the application.
- **AC voltage controllers or AC regulators:** They are employed to get a variable AC voltage of the same frequency from a single phase or three phase supplies. Some such controllers are Auto transformers, Transformers with various taps and Converters using Power electronics devices.
- **DC to DC converters:** They are used to get variable DC voltage from a fixed DC voltage source using Power electronics devices. Smooth step less variable voltage can be obtained with such converters.
- **Inverters:** They are employed to get variable voltage /variable frequency from DC supply using PWM techniques. Inverters also use the same type of Power electronics devices like MOSFETs, IGBTs, SCRs etc.
- **Cycloconverters:** They convert fixed voltage fixed frequency AC supply into variable voltage variable frequency supply to control AC drives.

They are also built using Power electronic devices and by using controllers at lower power level. They are single stage converter devices.

Control unit/Sensing unit: The control unit controls the operation of the Power converter based on the Input command and the feedback signal continuously

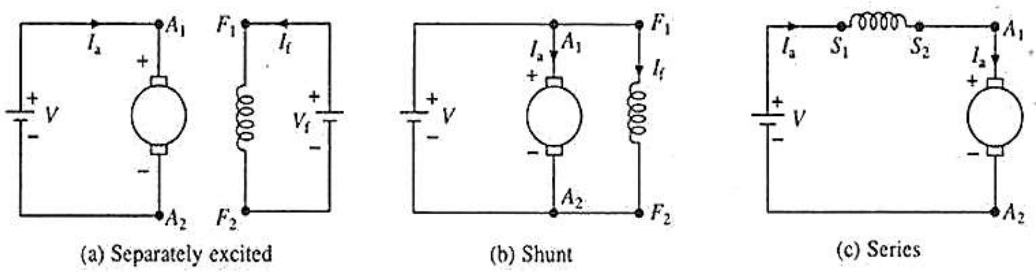


Figure 1-3. Basic Schematic diagrams of DC motors

- In a separately excited DC motor, the field and armature are connected to separate voltage sources and can be controlled independently.
- In a shunt motor the field and the armature are connected to the same source and cannot be controlled independently.
- In a series motor the field current and armature current are same and hence the field flux is dependent on armature current.

The Steady state equivalent circuit of a DC motor Armature is shown in the figure below.

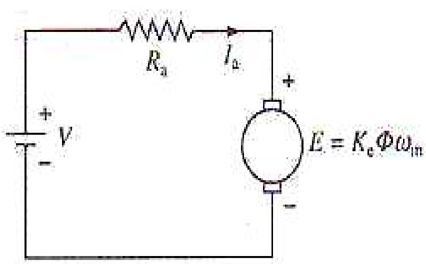


Figure 1-4. Steady state equivalent circuit of a DC Motor Armature

Resistance R_a is the resistance of the armature circuit. For separately excited and shunt motors it is resistance of the armature winding and for series motors it is the sum of the field winding and armature winding resistances.

The output characteristics of DC motors (Torque/Speed characteristics): They can be obtained from the Motor's Induced voltage and torque equations plus the Kirchhoff's voltage law around the armature circuit and are given in table 1.1.

- The internal voltage generated in a DC motor is given by $E_b = K_a \emptyset \omega$
- The internal torque generated in a DC motor is given by $T = K_a \emptyset I_a$
- KVL around the armature circuit is given by $E_a = E_b + I_a R_a$

Where:

$\emptyset$: Flux per pole (Weber's)

I_a: Armature Current (Amperes)

E_a: Applied terminal voltage (Volts)

R_a: Armature resistance (Ohms)

ω: Motor speed (radiance / sec)

E_b: Armature back *EMF* (Volts)

T: Torque (N-m)

K_a: Motor Back EMF/Torque constant

From the above three equations we get the Basic general relation between Torque and speed as:

$$\omega = \left(\frac{E_a}{K_a \emptyset}\right) - \left(\frac{R_a}{K_a \emptyset}\right) . I_a \tag{1.1}$$

$$\omega = \left(\frac{E_a}{K_a \emptyset}\right) - \left[\frac{R_a}{(K_a \emptyset)^2}\right] \tau \tag{1.2}$$

1.6. Shunt and separately excited motors

In their case with a constant field current the field flux can be assumed to be constant and then (K_a. Φ) would be another constant K. Then the above Torque speed relations would become:

$$\omega = \left(\frac{E_a}{k}\right) - \left(\frac{ER_a}{k}\right) . I_a \tag{1.3}$$

$$\omega = \left(\frac{E_a}{k}\right) - \left(\frac{R_a}{k^2}\right) . \tau \tag{1.4}$$

The Speed/ Torque Characteristics of a DC Separately Excited Motor for rated terminal voltage and full field current are shown in the figure below. It is a drooping straight line.

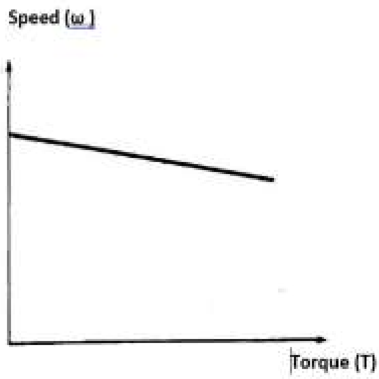


Figure 1-5. Speed/ Torque Characteristics of a DC Separately Excited Motor

The no load speed is given by the Applied armature terminal voltage and the field current. Speed falls with increasing load torque. The speed regulation depends on the Armature circuit resistance. The usual drop from no load to full load in the case of a medium sized motor will be around 5%. Separately excited motors are mostly used in applications where good speed regulation and adjustable speed are required.

Series Motor: In series motors the field flux Φ is dependent on the armature current $\boldsymbol{I_a}$ and can be assumed to be proportional to the armature current in the unsaturated region of the magnetization characteristic. Then

$$\emptyset = K_f I_a \tag{1.5}$$

And using this value in the three general motor relations given earlier we get

$$T = K_a \emptyset I_a = K_a K_f I_a^2 \tag{1.6}$$

$$\omega = \frac{E_a}{K_a K_f I_a} - \left(\frac{R_{af}}{K_a K_f}\right) \tag{1.7}$$

$$\omega = \frac{E_a}{\sqrt{K_{af}\tau}} - \frac{R_a}{K_{af}} \tag{1.8}$$

Where:

R_{af} is now the sum of armature and field winding resistances and,

$K_{af} = K_a . K_f$ is the total motor constant.

The Speed-Torque characteristics of a DC series motor are shown in the figure below.

1.7. Speed (ω) Torque (T)

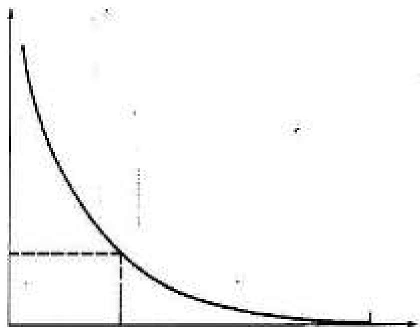


Figure 1-6. Speed-Torque characteristics of a DC series motor

- Series motors are suitable for applications requiring high starting torque and heavy overloads. Since Torque is proportional to square of the armature current, for a given increase in load torque the increase in armature current is less in case of series motor as compared to a separately excited motor where torque is proportional to only armature current. Thus, during heavy overloads power overload on the source power and thermal overload on the motor are kept limited to reasonable small values.

- According to the above Speed torque equation, as speed varies inversely to the square root of the Load torque, the motor runs at a large speed at light load. Generally, the electrical machines' mechanical strength permits their operation up to about twice their rated speed. Hence the series motors should not be used in such drives where there is a possibility for the torque to drop down to such an extent that the speed exceeds twice the rated speed.

1.8. DC Motor speed control:

There are two basic methods of control

- Armature Voltage Control (AVC) and
- Flux control

Torque speed curves of both SE (separately Excited) motors and series motors using these methods are shown in the figure below.

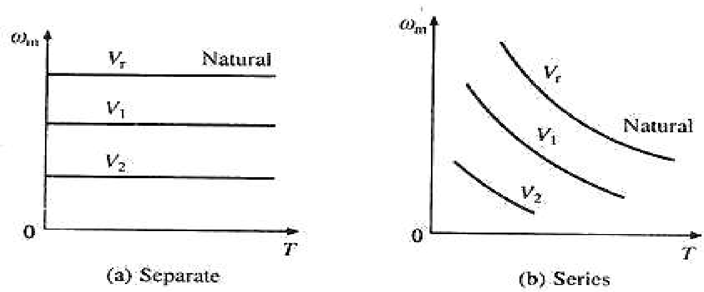


Figure 1-7. Torque speed curves with AVC: Vr (V_{rated}) > V1 > V2)

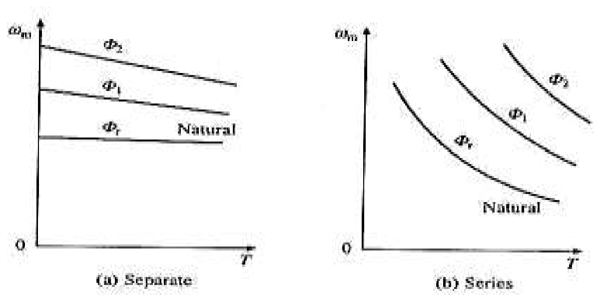


Figure 1-8. Torque speed curves with FC: Φ_r (Φ_{rated}) $> \Phi_1 > \Phi_2$)

1.8.1. Important features of DC Motor speed control:

- AVC is preferred because of high efficiency, good transient response, and good speed regulation. But it can provide speed control below base speed only because armature voltage cannot exceed the rated value.
- For speeds above Base speed Field Flux Control is employed. In a normally designed motor, the maximum speed can be twice the rated speed and in specially designed motors it can be up to six times the rated speed.
- AVC is achieved by Single and Three phase Semi & Full converters.
- FC in separately excited motors is obtained by varying the voltage across the field winding and in series motors by varying the number of turns in the field winding or by connecting a diverting resistance across the field winding.
- Due to the maximum torque and power limitations, DC Drives operating
    - With full field, AVC below base speed can deliver a constant maximum torque. This is because in AVC with full field, the Torque is proportional to I_a and consequently the torque that the motor can deliver has a maximum value.
    - With rated Armature Voltage, Flux control above base speed can deliver a constant maximum power. This is because at rated armature voltage, P_m is proportional to I_a and consequently the maximum power that can be developed by the motor has a constant value.
- These limitations are shown in the figure 1.9.

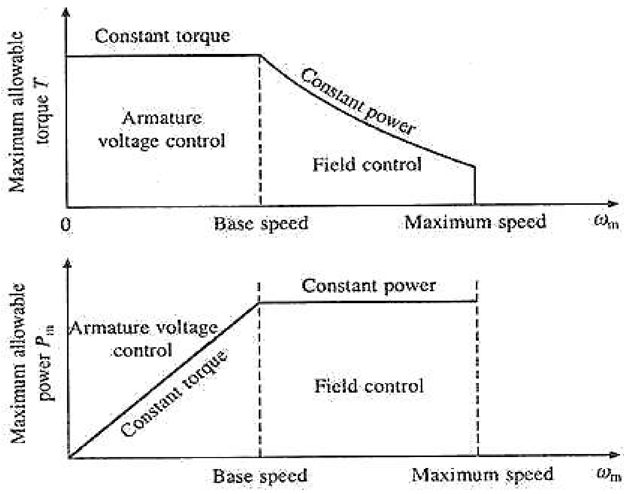


Figure 1-9. Torque and Power limitations in Combined Armature Voltage and Flux controls

1.9. Single phase Semi converter drives feeding a separately excited DC motor

Semi converters are one quadrant converters. i.e., they have one polarity of voltage and current at the DC terminals. The circuit diagram of Semi converter feeding a DC separately excited motor is shown in the figure below. It consists of Two controlled rectifiers (Thyristors $T1$ and $T2$) in the upper limbs and two Diodes $D1$ and $D2$ in the lower limbs in a bridge configuration along with a freewheeling diode as shown in the figure below. The armature voltage is controlled by a 1φ semi converter and the field circuit is fed from a separate DC source. The motor current cannot reverse since current cannot flow in the reverse direction in the thyristors. In Semi converters the DC output voltage and current are always positive. Therefore, in drive systems using semi converters reverse power flow from motor to AC supply side is not possible. The armature current may be continuous or discontinuous depending on the operating conditions and circuit parameters. The torque speed characteristics would be different in the two modes of conduction. We will limit our study to Continuous conduction mode in this chapter.

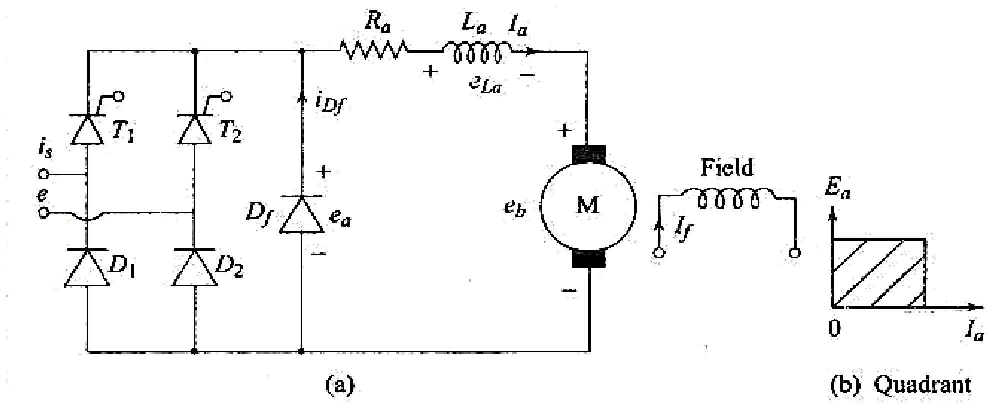


Figure 1-10. Single Phase Semi converter feeding a Separately Excited DC Motor

1.9.1. Performance of Semi Converter in Continuous Current Operation:

The voltage and current waveforms are shown in the figure below for operation in continuous current mode over the whole range of operation. $SCR\ T1$ is triggered at a firing angle α and $T2$ at the firing angle $(\pi + \alpha)$. During the period $\alpha < \omega t < \pi$ the motor is connected to the input supply through $T1$ and $D2$ and the motor terminal voltage e_a is the same as the input supply voltage 'e'. Beyond period π, e_a tends to reverse as the input voltage changes polarity. This will forward bias the freewheeling diode D_F and it starts conducting. The motor current i_a which was flowing from the supply through $T1$ is transferred to D_F ($T1$ gets commutated). Therefore, during the period $\pi < \omega t < (\pi + \alpha)$ the motor terminals are shorted through D_F making e_a zero.

As explained above, when the thyristor conducts during the period $\alpha < \omega t < \pi$, energy from the supply is delivered to the armature circuit. This energy is partially stored in the Inductance, partially stored as kinetic energy in the moving system and partially used up in the load. During the freewheeling period $\pi < \omega t < (\pi + \alpha)$ energy is recovered from the Inductance and is converted to mechanical form to supplement the Kinetic energy required to run the load. The freewheeling armature current continues to produce the torque in the motor. During this period no energy is feedback to the supply.

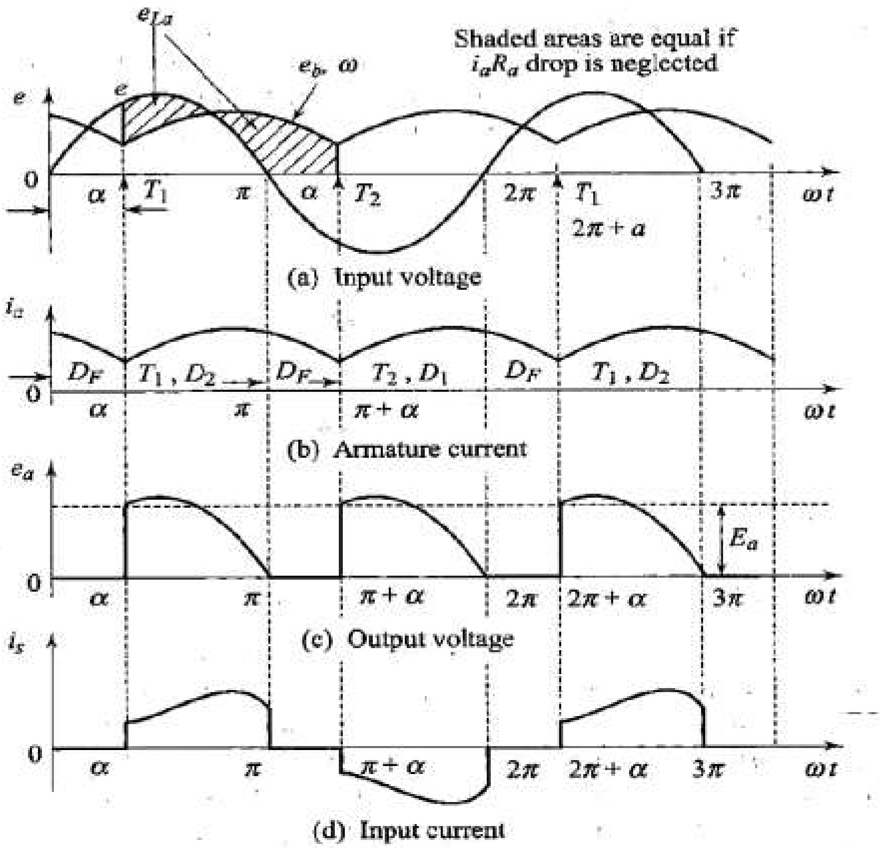


Figure 1-11. Voltage and Current waveforms for Continuous current operation in a single-Phase semi-controlled drive connected to a separately excited DC motor.

1.10. Torque Speed Characteristics of a Single-phase Semi Converter connected to DC separately excited motor

In terms of average voltages, KVL around the motor armature gives

$$E_a(\alpha) = E_b + I_aR_a = K_a\emptyset\omega + I_aR_a \quad (1.9)$$

$$\therefore \omega = \frac{|E_a\alpha - I_aR_a|}{K_a\emptyset} \qquad (1.10)$$

Assuming motor current to be continuous, the motor armature voltage as derived above for the single-phase semi converter is given by:

$$E_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} E_m sin\omega t d(\omega t) = \frac{E_m}{\pi}(1 + cos\alpha)$$

$$E_a(\alpha) = \frac{E_m}{\pi}(1 + cos\alpha) \qquad (1.11)$$

Using this in the above expression for speed **ω** we get

$$\omega = \left[\left(\frac{E_m}{\pi}\right)\frac{(1 + cos\alpha) - I_aR_a}{K_a\emptyset}\right] \qquad (1.12)$$

$$\omega = \left[\left(\frac{E_m}{\pi}\right)\frac{(1 + cos\alpha)}{K_a\emptyset}\right] - \left[\frac{I_aR_a}{K_a\emptyset} + \omega\right] \qquad (1.13)$$

$$\omega = \left[\left(\frac{E_m}{\pi}\right)\frac{(1 + cos\alpha)}{K_a\emptyset}\right] - \left[\frac{R_a}{(K_a\emptyset)^2}\right]\tau \qquad (1.14)$$

The resulting torque speed characteristics are shown in the figure 1-12.

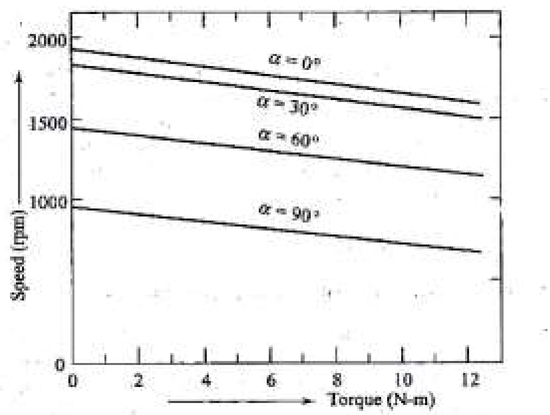


Figure 1-12. Torque Speed characteristics of a separately excited DC motor Connected to a single-Phase semi-controlled drive

1.11. Single Phase Full Converter Drive feeding a Separately Excited DC Motor

A full converter is a two-quadrant converter in which the output voltage can be bipolar but the current will be unidirectional since the Thyristors are unidirectional. A full converter feeding a separately excited DC motor is shown in the figure 1-13.

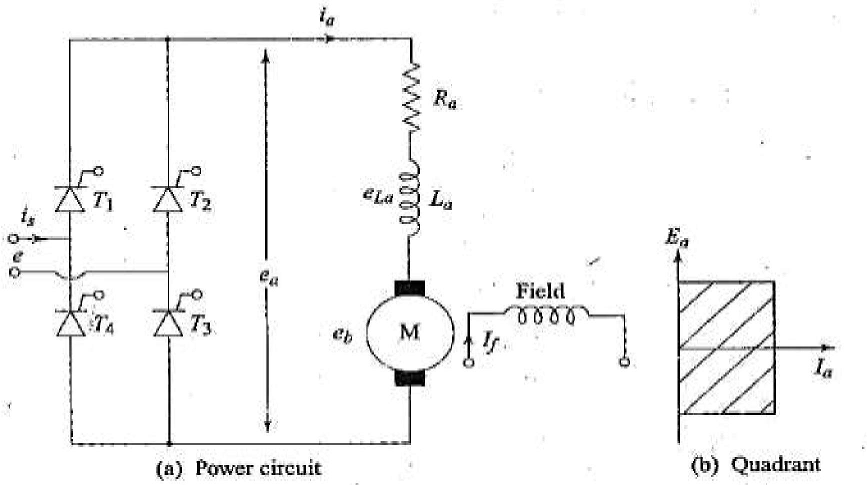


Figure 1-13. Single Phase full converter feeding a separately excited DC motor

In this all the four devices are thyristors $(T1\ to\ T4)$ connected in a bridge configuration as shown in the figure 1-13. The operation of the Full converter shown in the figure above is explained with the help of the waveforms shown below. Thyristors $T1$ and $T3$ are simultaneously triggered at a firing angle of **α** and thyristors T2 and T4 are triggered at firing angle $(\pi + \alpha)$. The voltage and current waveforms under continuous current mode are shown in the figure below. Figure shows the input voltage **e** and the voltage e_{La} across the inductance (shaded area). The triggering points of the thyristors are also shown in the figure 1-14.

As can be seen from the waveforms, the motor is always connected through the thyristors to the input supply. Thyristors T1 and T3 conduct during the interval

$\alpha < \omega t < (\pi + \alpha)$ and connect the supply to the motor. From (π+α) to α thyristors T2 and T4 conduct and connect the supply to the motor. At (π+α) when the thyristors T2 and T4 are triggered, immediately the supply voltage which is negative appears across the Thyristors T1 and T3 as reverse bias and switches them off. This is called natural or line commutation. The motor current i_a which was flowing from the supply through T1 and T3 is now transferred to T2 and T4. During α to π energy flows from the input supply to the motor (both e & i_s and e_a & i_a are positive signifying positive power flow). However, during the period π to $(\pi + \alpha)$ some of the motor energy is fed back to the input system. (e & i_s and similarly, e_a & i_a have opposite polarities signifying reverse power flow)

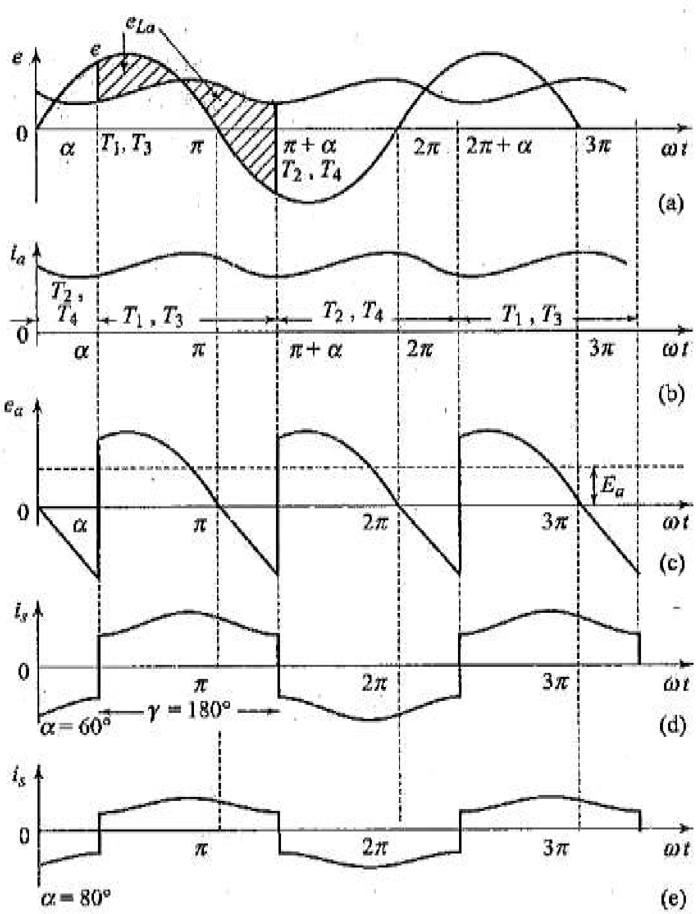


Figure 1-14. Voltage and Current waveforms for Continuous current operation in a single Phase fully controlled drive connected to a separately excited DC motor.

Torque Speed Characteristics of a DC separately excited motor connected to a Single-phase Full converter:

Assuming motor current to be continuous, the motor armature voltage as derived above for the single-phase full converter is given by:

$$E_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} E_m \sin \omega t. d(\omega t) = \frac{E_m}{\pi}[-cos\omega t]_{\alpha}^{\pi+\alpha}$$

$$E_{dc} = \frac{E_m}{\pi}[cos\alpha - cos(\pi + \alpha)]$$

$$E_{dc} = \frac{2E_m}{\pi} cos\alpha$$

$$E_a\alpha = \frac{2E_m}{\pi} cos\alpha$$

In terms of average voltages, KVL around the motor armature gives

$$E_a\alpha = E_b + I_aR_a$$

$$E_a\alpha = K_{a\emptyset}N + I_aR_a$$

And therefore, the average speed is given by:

$$\omega = \frac{[E_a\alpha - I_aR_a]}{K_a\emptyset}$$

In a separately excited DC motor:

$$T = I_aK_{a\emptyset}$$

And applying this relationship along with the above value of $E_a(\alpha\,)$ for the full converter in the above expression for the speed we get:

$$\omega = [\frac{(\frac{2E_m}{\pi})(\cos\alpha) - I_aR_a}{K_{a\varphi}}].$$

$$\omega = [\frac{\left(\frac{2E_m}{\pi}\right)(\cos\alpha)}{K_{a\varphi}}] - [\frac{I_a R_a}{K_{a\varphi}}]$$

$$\omega = [\frac{\left(\frac{2E_m}{\pi}\right)(\cos\alpha)}{K_{a\varphi}}] - [T.\frac{Ra}{(K_{a\varphi})^2}]$$

The no-load speed of the motor is given by:

$$\omega_{NL} = \frac{\left[\left(\frac{2E_m}{\pi}\right)(\cos\alpha)\right]}{Ka\varphi +} \quad (1.15)$$

where the torque T = 0

The resulting torque speed characteristics are shown in the figure 1-15.

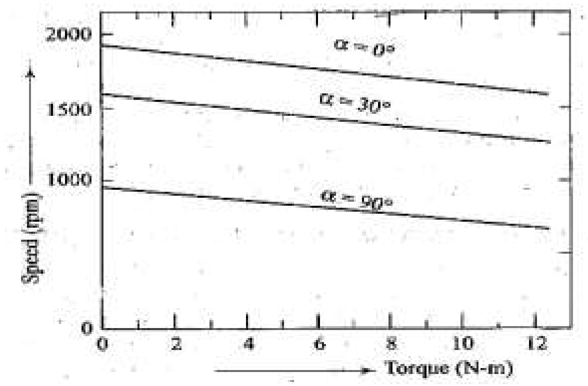


Figure 1-15. Torque Speed characteristics of separately excited DC motor Connected to a single Phase fully controlled drive at different firing angles.

1.12. Single Phase Converter Drives for DC Series Motors

Single-phase converter drives are widely used for controlling the speed of DC series motors, particularly in applications where a wide range of speed control and high starting torque are required. These drives convert a fixed AC input voltage into a variable DC output voltage, which is then supplied to the DC series motor.

Figure 1-16 shows the scheme of a basic single phase speed control circuit connected to a DC series motor. As shown the field circuit is connected in series with the armature and the motor terminal voltage is controlled by a semi or a full converter.

- Series motors are particularly suitable for applications that require a high starting torque such as cranes hoists, elevators, vehicles etc.
- Inherently series motors can provide constant power and are therefore particularly suitable for traction drives.
- Speed control is very difficult with the series motor because any change in load current will immediately reflect in the speed change and hence for all speed control requirements separately excited motors will be used.

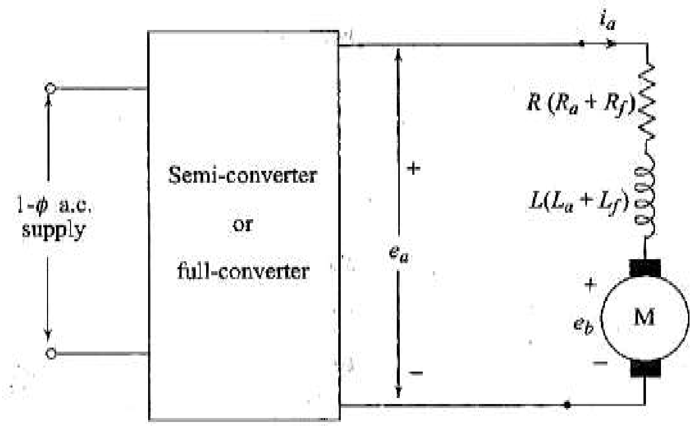


Figure 1-16. DC Series motor Power circuit

In the figure 1-16 the armature resistance Ra and Inductance La are shown along with the field resistance and inductance. The basic DC series motor equations are given below again for ease of reference

$$E_b = K_a.\Phi.\omega = K_a.K_f.I_a.\omega \text{ (since } \Phi = Kf.If = Kf.Ia\text{)}$$

$$E_b = K_{af}.I_a.\omega \;(where\ K_{af} = K_a.K_f)$$

$$T = K_a.\Phi.I_a = K_a.K_f.I_a^2 = K_{af}.I_a^2$$

$E_a = E_b + I_a . R_a$

$\omega = \frac{E_a}{K_{af} I_a} - (\frac{R_a}{K_{af}})$

$$\omega = \frac{E_a}{\sqrt{K_{af} T}} - \frac{R_a}{K_{af}} \tag{1.16}$$

1.12.1. Advantages of Single-Phase Converter Drives for DC Series Motors:

- **Simple and Cost-Effective:** Single-phase converters are relatively simpler in design and less expensive compared to three-phase converters, making them suitable for lower power applications.
- **High Starting Torque:** DC series motors naturally provide high starting torque, which is beneficial for heavy-duty applications.
- **Wide Speed Control Range:** By controlling the firing angle, a wide range of speed control can be achieved.
- **Good Performance at Low Currents:** Due to the series connection of field and armature, the back EMF in series motors decreases with armature current, which helps maintain continuous current flow even at lower currents, leading to better performance in those ranges.
- **Compact Size:** The overall drive system can be relatively compact.

1.12.2. Applications:

Single-phase converter drives for DC series motors are commonly found in applications requiring high starting torque and variable speed control, especially in the low to medium power range. Some typical applications include:

- **Traction Systems:** Electric locomotives, trolleys, and other electric vehicles.
- **Cranes and Hoists:** Where heavy loads need to be lifted and lowered with precise speed control.

- **Lifts and Elevators:** Requiring controlled acceleration and deceleration.
- **Mine Winders:** For lifting materials from mines.
- **Machine Tools:** Where variable speed is necessary for different machining operations.
- **Domestic Appliances:** Such as vacuum cleaners, hair dryers, and sewing machines (though often universal motors are used which behave like DC series motors on AC).
- **Small Industrial Drives:** In various low-power machinery.

1.13. Single Phase Semi Converter Drive connected to DC Series Motors:

The figure 1-17 shows the power circuit of a single-phase semi converter-controlled DC series motor.

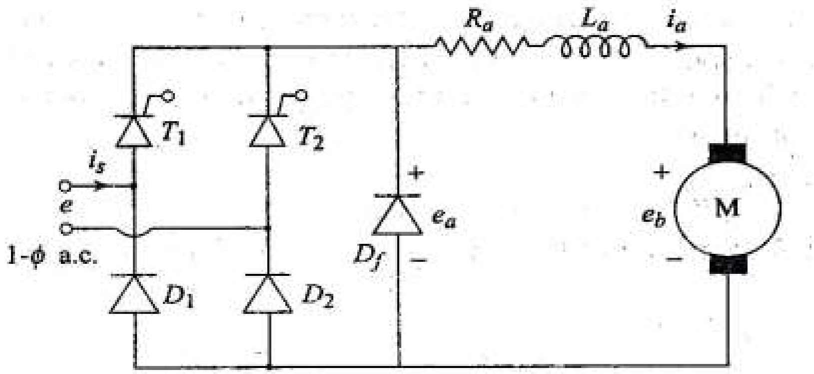


Figure 1-17. Power circuit of a Series motor connected to a Semi Controlled converter

Current and voltage waveforms for continuous motor armature current are shown in the figure below. When SCR is triggered at a firing angle **α** the current flows during the period α to (π + α) for continuous conduction.

In separately excited motors a large Back EMF is always present even when the armature current is absent. This back EMF E_b tends to oppose the motor current and so the motor current decays rapidly. This leads to discontinuous motor current over a wide range of operations. Whereas in series motors the back EMF is proportional to the armature current and so E_b decreases as I_a decreases. So, the motor current tends to be continuous over a wide range of operations. Only at high speed and low current is the motor current is likely to become discontinuous. Like in earlier semi converters Freewheeling diode is connected across the converter output as shown in the figure above. Freewheeling action takes place during the interval π to (π + α) in continuous current operation.

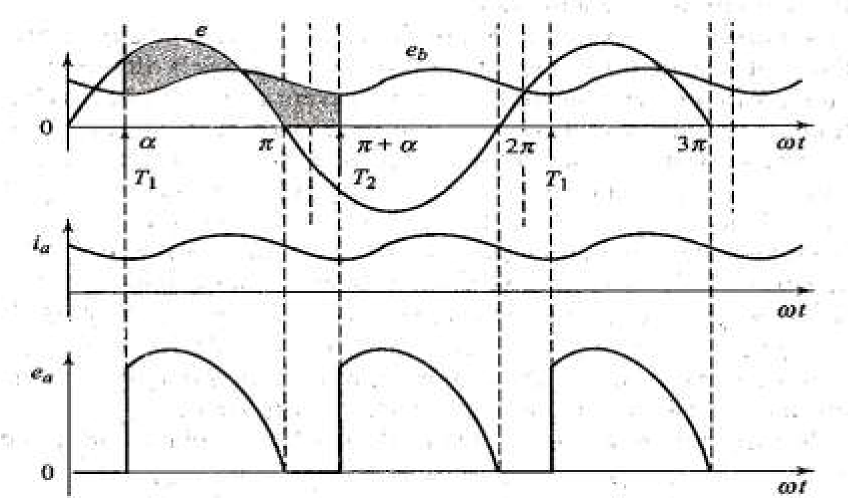


Figure 1-18. DC Series motor Semi Converter waveforms in continuous current operation.

In phase-controlled converters for Series motors, the current is mostly continuous and the motor terminal voltage can be written as

$$E_a = \frac{E_m}{\pi}(1 + cos\alpha) = I_a R_a + E_b = I_a R_a + K_{af}.I_a.\omega$$

Hence from the above equation the average speed can be written as

$$\omega = \frac{E_m}{\pi}\frac{(1+cos\alpha)}{K_{af}I_a} - \frac{R_a I_a}{K_{af}I_a}$$

$$\omega = \frac{E_m}{\pi}\frac{(1 + cos\alpha)}{\sqrt{K_{af}T}} - \frac{R_a}{K_{af}} \qquad (1.17)$$

The torque Speed characteristics under the assumption of continuous and ripple free current flow are shown in the figure below for different firing angles α.

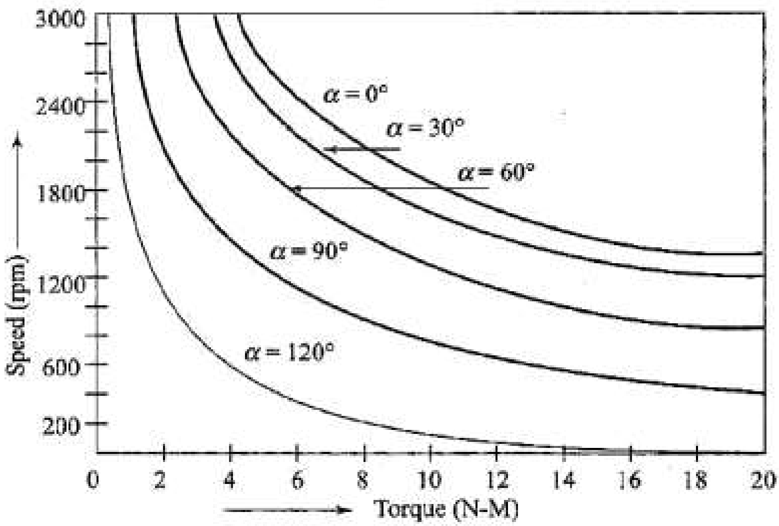


Figure 1-19. Torque Speed Characteristics of a DC Series motor controlled by a Single-phase Semi converter

1.13.1. Advantages

- **Simplicity and Cost-Effectiveness:** Compared to full converters, semi-converters use fewer controlled devices (thyristors), making them simpler in design and generally more economical.
- **Improved Power Factor (compared to full converters at low speeds):** The freewheeling action of the diode improves the displacement factor of the line current.
- **Reduced Motor Heating:** The presence of the freewheeling diode reduces the RMS current in the motor, leading to less heating compared to a full converter, especially at low speeds and light loads.
- **Continuous Current Operation:** The freewheeling diode promotes continuous conduction of the armature current over a wider operating range, particularly beneficial for series motors where the back EMF decreases with current, aiding continuous conduction. This results in smoother torque.
- **Suitable for One-Quadrant Applications:** Ideal for applications where

the motor only needs to operate in one direction and regenerative braking is not required.

1.13.2. Disadvantages

- **One-Quadrant Operation:** The inability to reverse voltage or current means it cannot support regenerative braking, which limits its use in applications requiring rapid deceleration or energy recovery.
- **Pulsating Output:** The output DC voltage is pulsating, leading to ripple in the armature current. While the freewheeling diode helps, significant ripple can still occur, especially at low speeds and high firing angles.
- **Higher Harmonic Content:** The pulsating output can introduce higher harmonic content in the AC supply, potentially causing power quality issues and electromagnetic interference.
- **Limited Power Applications:** Single-phase semi-converters are generally used for lower to medium power DC motor drives. For high-power applications, three-phase converters are preferred due to smoother output and better efficiency.
- **Poor Speed Regulation at Light Loads:** Discontinuous conduction can still occur at light loads and high speeds, leading to poorer speed regulation.

1.13.3. Applications

Single-phase semi-converter drives for DC series motors are typically found in applications that require:

- Moderate speed control range.
- High starting torque.
- One-directional operation.
- No requirement for regenerative braking.

Common applications include:

- **Traction systems (e.g., small electric vehicles, trams):** Where high starting torque is essential.
- **Cranes and Hoists:** For lifting and lowering operations, though typically heavier duty applications might use full converters for better control.
- **Fans and Pumps:** Where precise speed control is needed without frequent stops or reversals.
- **Small Industrial Drives:** For general-purpose motor control in various manufacturing processes.

1.14. Single Phase full converter drive connected to a DC series motor:

A single-phase full converter drive connected to a DC series motor is a common arrangement for controlling the speed of DC series motors in various industrial applications. Here's a breakdown of its components, operation, characteristics, and applications:

1.14.1. Components

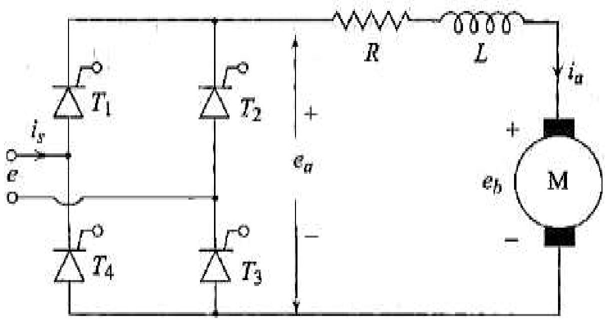


Figure 1-20. Power circuit of a Series motor connected to a fully controlled converter

- **Single-Phase Full Converter (Thyristor Bridge):** This is the power electronic circuit that converts the AC input voltage from the mains supply into a variable DC output voltage. It typically consists of four thyristors (SCRs) arranged in a full-bridge configuration.

- **DC Series Motor:** This type of DC motor has its field winding connected in series with the armature winding. This means the field current is the same as the armature current ($I_f = I_a$). Series motors are known for their high starting torque and good speed regulation under varying loads.

The figure 1.20 shows the power circuit of a single phase Fully controlled converter connected to a DC series motor.

Thyristors T1 & T3 are simultaneously triggered at α and T2 & T4 are simultaneously triggered at (π + α). Current and voltage waveforms for continuous motor armature current are shown in the figure below. When SCR is triggered at a firing angle α the current flows during the period α to (π + α) for continuous conduction.

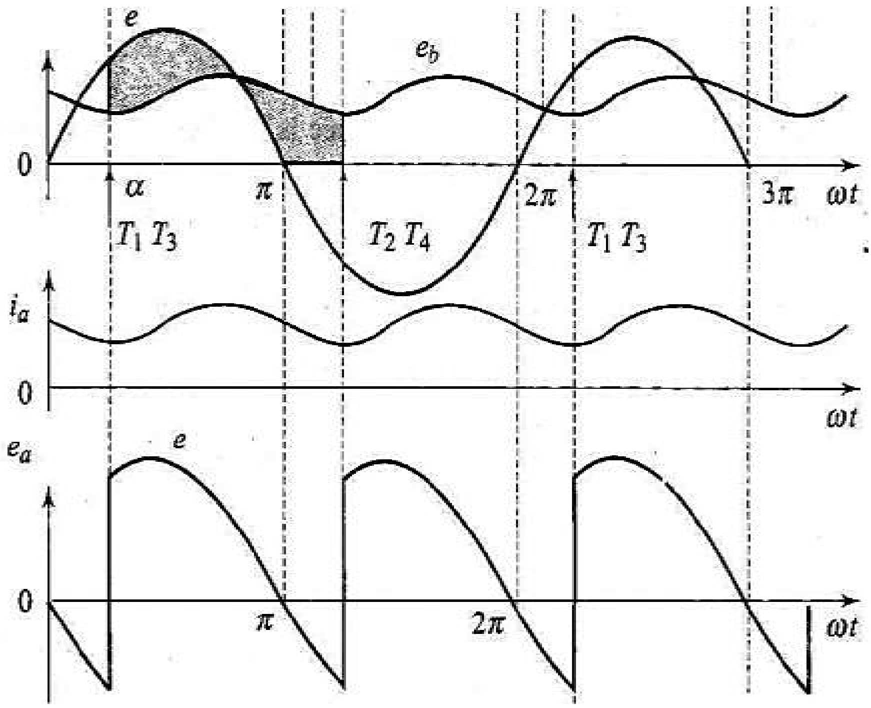


Figure 1-21. DC Series motor Full converter waveforms in continuous current operation.

The motor terminal voltage can be written as

$$E_a = \frac{2E_m}{\pi} cos\alpha = I_a R_a + E_b = I_a R_a + K_{af} I_a \omega$$

Hence from the above equation the expression for average speed can be written as

$$\omega = \frac{\left(\frac{2E_m}{\pi}\right)(\cos\alpha)}{K_{af}.Ia}] - [(R_a . \frac{I_a}{K_{af}.Ia})]$$

$$\omega = \frac{\left(\frac{2E_m}{\pi}\right)(cos\alpha)}{\sqrt{K_{af}.T}}] - \left[\left(\frac{R_a}{K_{af}}\right)\right] \#(\mathbf{1.18})$$

The torque Speed characteristics under the assumption of continuous and ripple free current flow are shown in the figure below for different firing angles α.

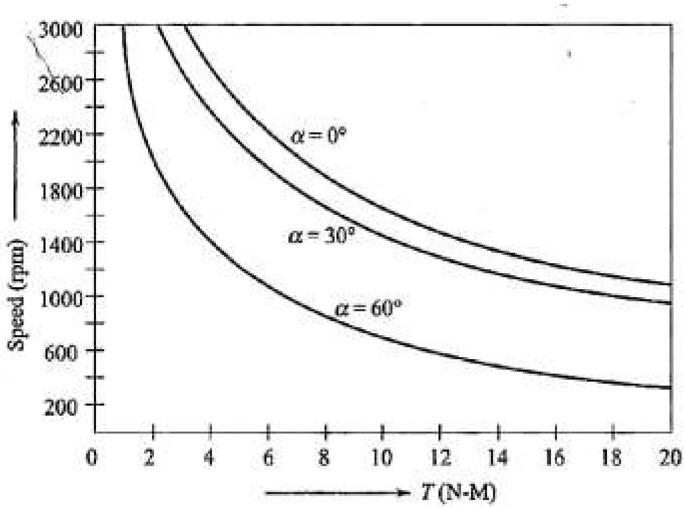


Figure 1-22. Torque Speed characteristics of a Series motor connected to a fully controlled converter

1.14.2. Characteristics:

- **Variable Speed:** The primary characteristic is the ability to achieve variable speed control of the DC series motor by adjusting the firing angle.

- **High Starting Torque:** DC series motors inherently provide high starting torque, which is beneficial for applications requiring heavy loads at startup.
- **Speed-Torque Relationship:** The speed of a series motor is inversely proportional to the square of the armature current (approximately). This means as the load increases (and thus armature current increases), the speed drops significantly. The converter allows for control over this characteristic.
- **Current Ripple:** The output of a single-phase full converter is pulsating DC, which introduces ripple in the armature current. This ripple can lead to increased motor losses and poorer commutation. An inductor in series with the armature can help smooth the current.
- **Power Factor:** The power factor of the system can be low, especially at high firing angles (low speeds), due to the phase displacement between voltage and current and harmonic distortion.

1.14.3. Applications:

Single-phase full converter drives connected to DC series motors are well-suited for applications that require:

- **High Starting Torque:** Their ability to provide high starting torque makes them ideal for:
    - **Traction applications:** Electric trains, trams, and some electric vehicles.
    - **Cranes and Hoists:** For lifting heavy loads.
    - **Elevators:** Providing strong initial lift.
    - **Conveyors:** Moving heavy materials.
- **Variable Speed Control:** Where precise speed control is needed over a certain range.
- **Cost-effectiveness:** For low to medium power applications, single-phase

drives are often simpler and less expensive than three-phase alternatives.

Summary:

- In single phase converters output ripple frequency is 100 Hz. (Both semi and full)
- Semi converters are one quadrant converters. i.e., they have one polarity of voltage and current at the DC terminals. In this as firing angle varies from 0 to 180^0 DC output varies from maximum ($2E_m/\pi$) to zero.
- A full converter is a two-quadrant converter in which the output voltage can be bipolar but the current will be unidirectional since the thyristors are Unidirectional. In this as firing angle varies from 0 to 180^0 DC output varies from maximum ($2E_m/\pi$) to ($-2E_m/\pi$)
- Separately excited motors are mostly used in applications where good speed regulation and adjustable speed are required.
- Series motors are suitable for applications requiring high starting torque and heavy overloads.
- In case of series motors, Since Torque is proportional to square of the armature current, for a given increase in load torque the increase in armature current is less as compared to separately excited motors where torque is proportional to only armature current.
- There are two basic methods of speed control. Armature Voltage Control and Flux Control.
- AVC is used for speeds below base speeds and FC for speeds above base speed.
- Due to the maximum torque and power limitations DC Drives operating
  - With full field, AVC below base speed can deliver a maximum constant torque and
  - With rated Armature Voltage, Flux control above base speed can deliver a maximum constant power.
- AVC is achieved by Single and three phase Semi & Full converters.

- FC in separately excited motors is obtained by varying the voltage across the field winding and in series motors by varying the number of turns in the field winding or by connecting a diverting resistance across the field winding.

Important formulae and equations:

The basic DC motor equations:

The internal voltage generated in a DC motor is given by $E_b = K_a.\emptyset\omega$
The internal Torque generated in a DC motor is given by: $T = K_a.\Phi.I_a$
KVL around the armature circuit is given by: $E_a = E + I_a.R_a$

Torque speed relations in semi converter:

DC separately excited motor: $\left[\frac{E_m}{\pi}\frac{(1+cos\alpha)}{K_a\emptyset}\right] - \left[\frac{R_a}{(K_a\emptyset)^2}\right]\tau$

DC series motor: $\omega = \left[\frac{E_m}{\pi}\frac{(1+cos\alpha)}{\sqrt{K_{af}T}}\right] - \left[\frac{R_a}{K_{af}}\right]$

Torque speed relations in Full converter:

DC separately excited motor: $\left[\frac{2E_m}{\pi}\frac{(cos\alpha)}{K_a\emptyset}\right] - \left[\frac{R_a}{(K_a\emptyset)^2}\right]\tau$

DC series Motor: $\omega = \left[\frac{2E_m}{\pi}\frac{(cos\alpha)}{\sqrt{K_{af}T}}\right] - \left[\frac{R_a}{K_{af}}\right]$

Example 1-1:

A separately excited D.C. motor is fed from a 230 V, 50 Hz supply via a single-phase, half –controlled bridge rectifier. Armature parameters are: inductance 0.06 H, resistance 0.3 Ω, the motor voltage constant is K_a = 0.9 V/A rad/s and the field resistance is R_F = 104 Ω. The filed current is also controlled by semi converter and is set to the maximum possible value. The load torque is T_L = 50 N-m at 800 rpm. The inductances of the armature and field circuits are sufficient enough to make the armature and filed current continuous and ripple free.

Compute: (i) The field current (ii) The firing angle of the converter in the armature circuit

Solution:

i) First point to be noted is since the units of K_a are V/A rad/sec the basic governing equations for back emf E_b and Torque T will become: $E_b = K_{af}.I_f.\omega$ and $T = K_{af}.I_f.I_a$ where K_{af}.is to be taken as the given $K_a = 0.9\, V/A\, rad/s$

ii) For single-phase semi converter controlled $d.c.$ drive, we can write the expression for field supply voltage as

$$E_f = \frac{E_m}{\pi}(1 + cos\alpha)$$

So, the maximum field voltage and current are obtained when firing angle α =0. i.e.,

$$\therefore E_f = \frac{2E_m}{\pi}$$

Hence Field voltage $E_f = \frac{2E_m}{\pi} = \frac{2\times\sqrt{2}\times 230}{\pi} = 207.07\, V$ V.

And filed current $I_f = \frac{E_f}{R_f} = \frac{207.07}{104} = 1.99A$

iii) Now, we can first find out armature current from the relation

$$I_a = \frac{T}{K_a I_f} = \frac{50}{0.9\times 1.99} = 27.92A$$

And then back emf from the relation:

$$E_b = K_a\, \omega\, I_f = 0.9 \times \left(800 \times \frac{2\pi}{60}\right) \times 1.99 = 150.04V$$

Hence finally we can find out armature voltage from the relation:

$$E_a = E_b + I_a\, R_a = 150.04 + 27.92 \times 0.3 = 158.42\, V.$$

But applied armature voltage from a single-phase semi converter is given by the equation $E_a = \frac{E_m}{\pi}(1 + cos\alpha$ and equating this to the above required armature voltage of 158.42 we get $\frac{\sqrt{2}\times 230}{\pi}(1+cos\alpha) = 158.42$ from which we get α = 58^0

Example 1-2:

The speed of a $10\,HP, 210\,V, 1000\,rpm$ separately excited $D.C.$ motor is controlled by a single-phase full-converter. The rated motor armature current is 30 A, and the armature resistance is $R_a = 0.25\,\Omega$. The $a.c.$ supply voltage is 230 V. The motor voltage constant is $K_a\Phi = 0.172\,V/rpm$. Assume that sufficient inductance is present in the armature circuit to make the motor current continuous and ripple free. For a firing angle α = 45^0, and rated motor armature current, determine: 1) The motor torque 2) Speed of the motor at Rated armature current.

Solution:

1) *The motor Torque:* can be found out directly by using the relation $T = K_a\,\Phi I_a$.

But the constant $K_a\,\Phi$ is same in the relations for torque and back emf if it is $\mathrm{V/Rad/sec}$ in back emf and $\mathrm{N-m/A}$ in torque**.** But it is given in $\mathrm{V/RPM}$. Hence it is first converted to V/Rad/sec and then used in the expression for torque.

The units of the $K_a\,\Phi\,(V/Rad/sec) = K_a\,\Phi\,(V/RPM)\,x\,60/2\pi$

$= \frac{0.172\times 60}{2\pi}V - \frac{s}{rad} = 1.64V - s/rad$

Rated Motor Torque T_R at rated armature current $= K_a\,\Phi I_{aR}$

$= 1.64 \times 30 = 49.2\,N-m.$

2) *Speed of the Motor at Rated armature current:* The armature voltage in a fully controlled single-phase converter is given by:

$$E_a = \frac{2E_m}{\pi}cos\alpha = \frac{2\sqrt{2}\times 230}{\pi}\cos 45^0 = 146.42$$

(The given supply voltage of 230 V is RMS value and it is to be converted into E_m by multiplying by $\sqrt{2}$)

$E_b = E_a - I_{aR} R_a = 146.42 - (30 \times 0.25) = 138.92\,V.$

Speed, $N = \frac{E_b}{K_a \emptyset} = \frac{138.92}{0172} = 807.67\,rpm$

(Here $K_a \emptyset$ is used directly with the given units of V/RPM so that we can get directly speed N in RPM)

Chapter-2.

Control of DC Motors by Three Phase Converters

2.1. Introduction to Four quadrant operation of electric drives

An electrical drive has to operate in three modes. i.e., starting, steady state and braking. To achieve this in both directions (forward and reverse) four quadrant operation as shown in the figure below is required which shows the torque and speed coordinates for forward and reverse motions. Power developed by a motor is given by the product of speed and torque.

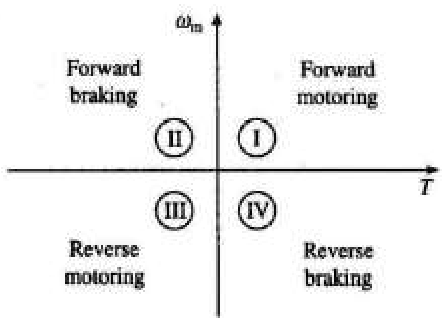


Figure 2-1. Four Quadrant operations of Electrical motors

2.1.1. Sign Conventions:

- Positive speed is FORWARD and negative speed is REVERSE.
- Sign of Power is the product of the signs of Torque and Speed. When it is positive it is MOTORING and when it is negative it is BRAKING.
- With this convention the four-quadrant operation of Motors is explained below. First with reference to the figure above and then with a practical example of Hoist (Lift)
- In Q-1 both *power & speed are positive (forward).* Motor works as a motor delivering mechanical energy to the load. Hence Q-1 operation is designated as *forward Motoring.*
- In Q-2 *power is negative but speed is positive (forward)*. Motor works as a brake opposing the motion. Hence Q-2 operation is designated as *Forward Braking*.
- In Q-3 *power is positive but speed is negative (reverse)*. Motor works as a motor delivering mechanical energy to the load. Hence Q-3 operation is designated as *Reverse Motoring.*
- In Q-4 both *power and speed are negative (reverse)*. Motor works as a brake opposing the motion. Hence Q-4 operation is designated as *Reverse Braking*.

For a better understanding of the four-quadrant operation of the drives and the related notations a practical example of a Hoist (Lift) operating in four quadrants is considered here as shown in the figure below. Directions of motor and load torques and direction of speed are marked with arrows.

A hoist consists of a rope wound on a drum coupled to the motor shaft. One end of the rope is connected to the carriage which carries men and/or material from one level to another level. Other end of the rope is connected to a counterweight to balance the carriage so as to distribute the load on the motor in both directions. *Weight of the counterweight is chosen such that it is higher than the empty carriage but lesser than the fully loaded carriage.*

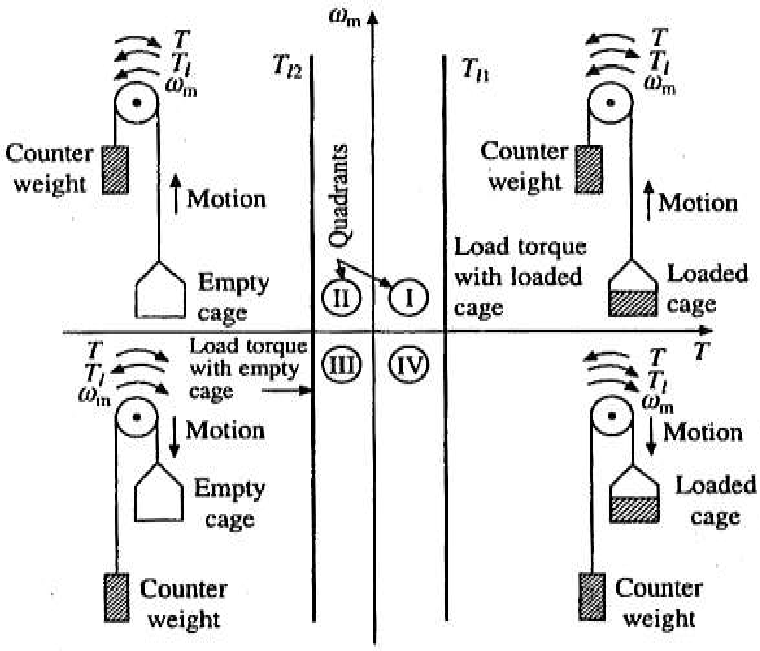


Figure 2-2. Typical Example of Four Quadrant operation of a Motor Driving a Hoist (Lift) load.

2.1.2. Speed and Torque Sign Conventions:

Are explained again with reference to the directions of Speed and Torque shown in the figure above.

- *Forward direction of motion or forward Speed* is considered to be the one which gives *Upward motion* to the carriage which is a result of Anticlockwise movement of the pulley (looking into the page)
- Similarly *Reverse direction of motion or Reverse Speed* is considered to be the one which gives *Downward ward motion* to the carriage which is a result of Clockwise movement of the pulley (looking into the page)
- Similarly, the *Torque* is considered to be *Positive* when acting *Anticlockwise* and *Negative* when acting *Clockwise.*
- The sign of the Power becomes the product of the sign of Torque and Speed.

Load torque characteristics are also shown in the diagram and are assumed to be constant. $\mathbf{T_{l1}}$ in quadrants 1 and 4 represents the speed torque characteristic of the loaded carriage. This torque is the difference of torques between loaded hoist and the counter weight and is positive since loaded carriage weight is higher than the counter weight. $\mathbf{T_{l2}}$ in quadrants 2 and 3 represents the speed torque characteristic of the empty carriage. This torque is the difference of torques between empty hoist and the counter weight and is negative since empty carriage weight is lesser than the counter weight.

In Quadrant -1 operation the loaded cage moves upwards corresponding to positive motor speed which in this case is anticlockwise movement of the pulley (looking into the page) This motion will be obtained if the motor produces positive torque in anti-clock wise direction equal to the magnitude of the load torque $\mathbf{T_{l1}}$**.** Since both Torque and Speed are Positive Power is also positive and this operation is Forward Motoring.

In Quadrant-4 operation the loaded cage moves downwards corresponding to a negative motor speed which in this case is clock wise movement of the pulley (looking into the page) Since the weight of a loaded cage is higher than the counterweight, it will come down due to the gravity itself. In order to limit the speed of the cage to a safe value, motor must produce a positive torque **T** equal to the load torque $\mathbf{T_{l1}}$ in anticlockwise direction**.** Since Torque is positive and Speed is Negative Power is Negative corresponding to Reverse Braking.

In Quadrant -2 operation the empty cage moves upwards corresponding to a positive motor speed which in this case is anticlockwise movement of the pulley. (Looking into the page) Since the weight of counterweight is higher than the weight of an empty cage, it will automatically move upwards. In order to limit the speed of the cage to a safe value, motor must produce a braking torque **T** equal to the load torque $\mathbf{T_{l2}}$ in clockwise (negative) direction. Since Torque is negative and Speed is positive the Power is Negative corresponding to Forward Braking.

In Quadrant -3 operation, empty cage is lowered. Since an empty cage weight is lesser than the counter weight, the motor must produce a negative torque i.e., in clockwise direction. Since both Speed and Torque both are negative, Power is positive and this operation becomes Reverse Motoring.

2.2. Starting of a DC shunt motor

Maximum current that a DC motor can safely carry is mainly limited by the maximum current that can be commutated without sparking. For normally designed machines twice the rated current can be allowed and in specially designed machines it can be up to 3.5 times the rated current.

During starting when the motor is standstill, the motor back emf will be zero and the only resistance that can limit the current is the armature resistance, which is quite small for almost all DC motors. Hence if a DC motor is started with full rated voltage applied to its terminals, then a very large current will flow and damage the motor due to heavy sparking in the commutator and heating of the winding. Hence the current is to be limited to a safe value during starting.

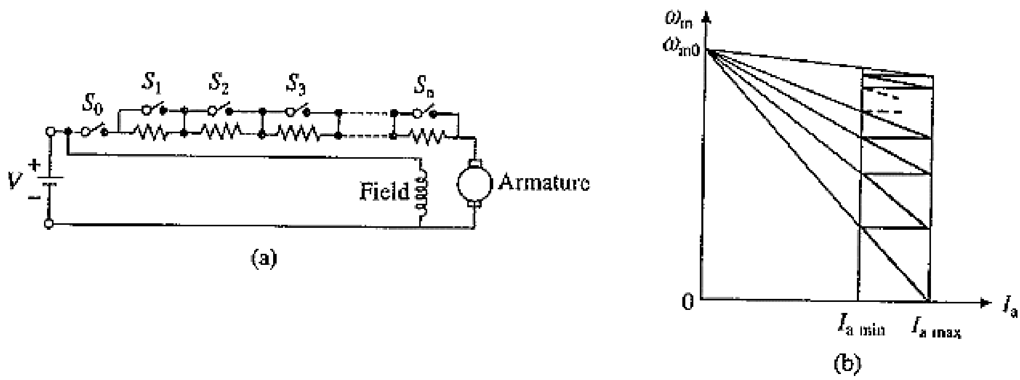


Figure 2-3. Starting of a DC Shunt motor

In closed loop speed controllers where *Speed and current controllers* are used the current can be limited to a safe value during starting. But in systems without such controllers a variable resistance controller such as the one shown in figure below is used during starting to limit the current. As the back emf increases with gradual increase in speed, section by section resistances will be removed either manually or remotely with the help of contactors so as to keep the current within the maximum and minimum limits.

2.3. Braking

An electrical drive has to operate in three modes i.e., steady state, starting and braking during both forward and reverse directions. *Braking* operation is required in two cases.

- For reducing the speed (deceleration) while the drive is operating in Forward (Quadrant-1) or Reverse (Quadrant-3) motoring modes. *Steady state is reached when the motoring torque is equal to the load torque*
- While driving an Active load. That means when the load assists the drive motion [for e.g., moving a loaded hoist in the down ward direction (Reverse braking: quadrant-4) or moving an unloaded hoist in the upward direction (Forward braking: quadrant -2)]. *Steady state is reached when the braking torque is equal to the load torque.*

In both the cases braking can be achieved by mechanical braking. But it has lot of disadvantages: Frequent maintenance like replacement of brake shoes/lining, lower life, wastage of braking power as heat et. These disadvantages are overcome by Electrical braking but many a times mechanical braking also supplements the electrical braking for reliable and safe operation of the drive.

During electric braking the motor works as a generator developing a torque which opposes the rotational motion. There are three types of electrical braking.

- Regenerative braking
- Dynamic or Rheostatic braking and
- Plugging or Reverse voltage braking.

2.3.1. Regenerative Braking:

In this, the generated energy is supplied to the source. For this to happen, the following conditions should be satisfied:

$|E_b| > |E_a|$ *and* negative I_a

The concept of regenerative braking can be explained by considering a fully controlled Rectifier connected to a DC separately excited motor as shown in the figure (a) below.

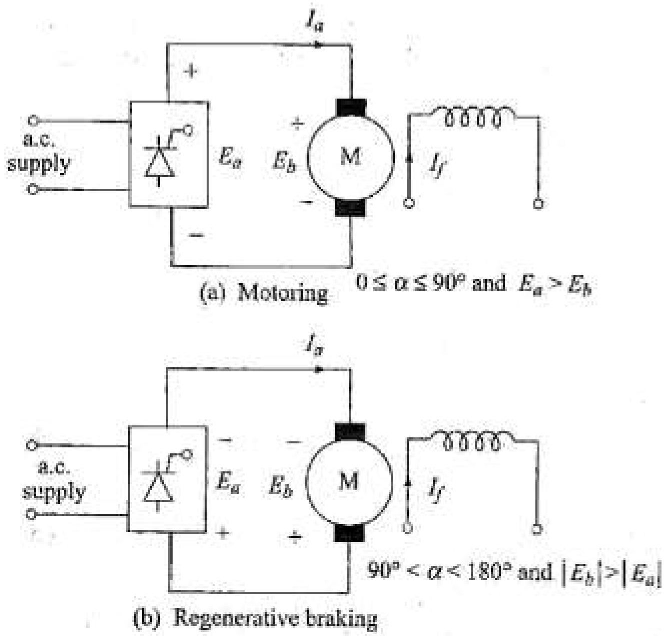


Figure 2-4. Two quadrant operations of a Fully Controlled rectifier feeding a DC separately excited motor

The polarities of output voltage, back emf and armature current are shown in the figure (a) above for the motoring operation in the forward direction. The converter output is positive with firing angle in the range $0° \leq \alpha \leq 90°$. With these polarities the converter supplies power to the motor which is converted to mechanical energy. Direction of power flow can be reversed if the direction of current flow is reversed. But this is not possible because the converter can carry current in only one direction. Then the only method available for reversal of power flow is by the following steps.

- Reverse the Converter output voltage E_a
- Also reverse the Back emf E_b with respect to the converter terminals
- And make $|E_b| > |E_a|$ as shown in fig (b). Out of these three steps
    - *Step 1*. i.e., the rectifier voltage E_a can be reversed by making $\alpha > 90^0$
    - *Step.3*. i.e., the condition $|E_b| > |E_a|$ can be satisfied by choosing a value of α in the range $90^0 \geq \alpha \leq 180^0$
    - *Step2*. The reversal of motor emf with respect to rectifier terminals can be done by any of the following changes.
        - The motor armature terminals can be reversed w.r.to the converter terminals using a reversing switch with the motor still running in the forward direction. (With contactors or thyristors as shown in the figure below) This gives forward regeneration.
        - The field current may be reversed with the motor running in the forward direction and this also gives forward regeneration without any changes in the armature connections.

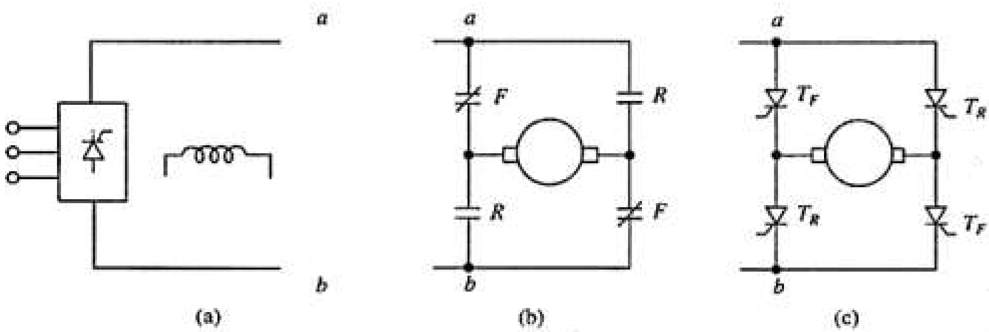


Figure 2-5. Four quadrant operations with a single converter and a reversing switch

Regenerative braking cannot be obtained

- If the drive runs in the forward direction only and there is no arrangement for the reversal of either the armature or the field.
- If the converter shown above is a Semi converter.

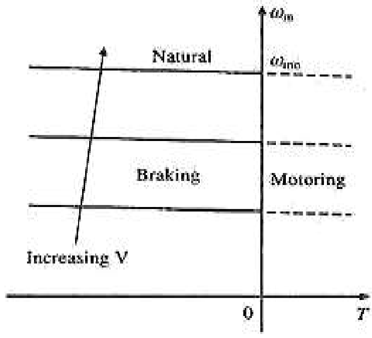


Figure 2-6. Regenerative Braking Characteristics of a Separately excited Motor

2.4. Dynamic Braking:

Dynamic braking is a widely used method in electrical drives to quickly and efficiently slow down or stop electric motors. It works by converting the kinetic energy of the rotating motor and its load into electrical energy, which is then dissipated, typically as heat.

In dynamic braking, the motor armature is disconnected from the source voltage and connected across a high wattage resistance R_B. The generated energy is dissipated in the Braking and armature resistances. The braking connections are shown below for DC separately excited motor and DC series motor.

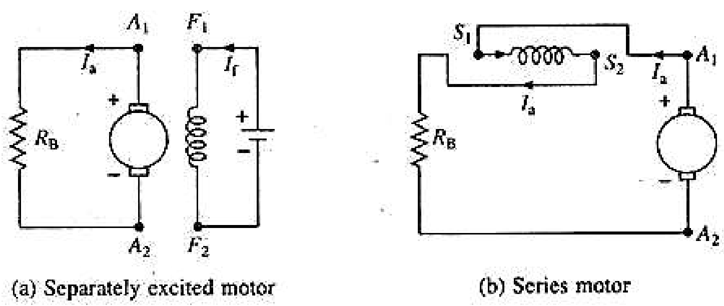


Figure 2-7. Connections during Dynamic Braking

In the case of a series motor, it can be seen that the field terminal connections are reversed such that the field current continues to flow in the same direction so that the field assists the residual magnetism. Figure below shows the Speed- Torque curves for both type of motors and the transition from Motoring to Braking.

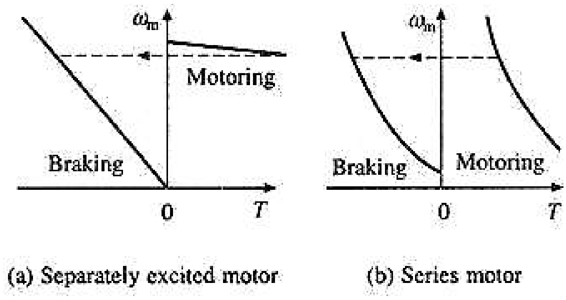


Figure 2-8. Speed-Torque curves during Dynamic Braking

2.4.1. How Dynamic Braking Works

When an electric motor is actively driving a load, it draws power from the supply. However, when the motor needs to slow down or stop, especially with a high inertia load (like a heavy flywheel or a descending crane), the load can actually drive the motor. In this scenario, the motor transitions from acting as a "motor" to acting as a "generator."

As a generator, the motor produces electrical energy. If this energy isn't managed, it can lead to an uncontrolled increase in the DC bus voltage of the drive system (e.g., a Variable Frequency Drive - VFD). Dynamic braking addresses this by:

- **Disconnecting from the power source (or modifying the circuit):** The motor is typically isolated from its regular power supply.
- **Connecting to a braking resistor:** The generated electrical energy is then shunted to an external braking resistor.
- **Dissipating energy as heat:** The braking resistor converts the electrical energy into heat, which is then dissipated into the atmosphere. This acts as a "load" on the generating motor, creating a braking torque that opposes the motor's motion, thereby slowing it down.

2.4.2. Types of Dynamic Braking:

While dynamic braking primarily involves dissipating energy as heat, there are variations depending on the motor type and how the braking is achieved:

- **Rheostatic Braking (most common form of dynamic braking):** This is the core concept where the motor's generated energy is dissipated in a resistor. It's often associated with DC motors where the armature is disconnected from the supply and connected across a resistance. For AC motors with VFDs, a "brake chopper" unit typically controls the flow of regenerated energy to an external dynamic braking resistor (DBR).
- **DC Dynamic Braking (for AC Induction Motors):** In this method, the stator windings of an AC induction motor are connected across a DC supply when braking. This creates a stationary magnetic field, and as the rotor rotates, it cuts this flux, inducing AC currents in the rotor. The generated energy is then dissipated in the rotor circuit's resistance.
- **AC Dynamic Braking:** This involves feeding the AC motor with a single-phase AC supply while disconnecting one phase. The motor then works under an unbalanced condition, and braking torque is produced.
- **Self-Excited Braking Using Capacitors:** In some cases, capacitors can be used to achieve self-excitation in the motor during braking, leading to energy dissipation.
- **Zero Sequence Braking:** The three phases of the stator are connected in series across either a single AC or DC source. This creates a zero-sequence current, and braking torque is generated.

2.4.3. Important Distinction: Dynamic Braking vs. Regenerative Braking

It's crucial to distinguish dynamic braking from *regenerative braking:*

- **Dynamic Braking:** Dissipates the regenerated electrical energy as heat in resistors. The energy is *wasted*.

- **Regenerative Braking:** Feeds the regenerated electrical energy back into the power supply system (e.g., the grid). This is more energy-efficient as the energy is *reused*.

While regenerative braking is more efficient, it's not always feasible or cost-effective, and dynamic braking remains a vital and often simpler solution for many applications.

2.4.4. Advantages of Dynamic Braking:

- **Faster and Controlled Stopping:** Allows for rapid and controlled deceleration of the motor and load, which is critical for safety and precision in many applications.
- **Reduced Wear and Tear:** Minimizes the reliance on mechanical friction brakes, extending the lifespan of brake components and reducing maintenance.
- **No External Power Required for Braking:** Once the motor acts as a generator, it creates its own braking force.
- **Simplicity:** Often simpler to implement than regenerative braking, especially in smaller systems.
- **Reliability:** Provides a reliable braking solution, even in emergency situations.

2.4.5. Disadvantages of Dynamic Braking:

- **Energy Loss:** The primary disadvantage is that the regenerated energy is dissipated as heat and is wasted, leading to lower overall energy efficiency compared to regenerative braking.
- **Heat Management:** Requires proper sizing and cooling of the braking resistors to prevent overheating and potential damage. This can add to the system's size and complexity.
- **Cannot Hold Stationary:** Dynamic braking cannot hold a load stationary; a mechanical brake is still required for holding applications.

- **Braking Torque Decreases with Speed:** As the motor slows down, the generated voltage and thus the braking torque decrease, meaning it's less effective at very low speeds.

2.4.6. Applications of Dynamic Braking:

Dynamic braking is widely used in various industrial and transportation applications where rapid and controlled deceleration is essential:

- **Cranes and Hoists:** Ensures safe and controlled lowering and stopping of heavy loads.
- **Elevators and Escalators:** Provides smooth and precise stopping for passenger safety and comfort.
- **Conveyor Belts:** Allows for quick stops in emergencies or for controlled material handling.
- **Centrifuges:** Enables rapid deceleration of high-speed rotating equipment.
- **Fans:** Used for controlled shutdown to prevent overspeeding.
- **Industrial Machinery:** Applicable in various machines requiring frequent or rapid stopping.
- **Electric and Hybrid Vehicles (especially in older designs or as a backup to regenerative braking):** Helps in slowing down the vehicle and reducing wear on friction brakes.
- **Railcars and Locomotives (rheostatic braking):** Dissipates energy in onboard resistors for braking, reducing wear on mechanical brakes.

2.5. Plugging

Plugging involves reconnecting the motor to the supply in such a way that it develops a torque in the opposite direction to its current rotation. This creates a strong braking force that rapidly slows down the motor and the connected load.

- **For DC Motors:** When a DC motor is running, if you reverse the polarity of the armature terminals (while keeping the field polarity the same), the back EMF (electromotive force) of the motor will now act in the same direction as the supply voltage. This results in a very large reverse current flowing through the armature, creating a high braking torque. To prevent excessive current and damage, an external resistance is usually connected in series with the armature.
- **For AC Induction Motors:** Plugging can be achieved by interchanging the connections of two phases of the three-phase supply. This reverses the direction of the rotating magnetic field, causing the motor to develop a braking torque against its current rotation.

In a DC separately excited motor Supply voltage is reversed so that it assists the Back EMF in forcing the Armature current in the reverse direction. In a Series motor Instead of supply voltage, armature alone is reversed so that the field current direction is not changed. In addition, like in dynamic braking, a Braking resistor R_B is also connected in series with the Armature to limit the current as shown in the figure below.

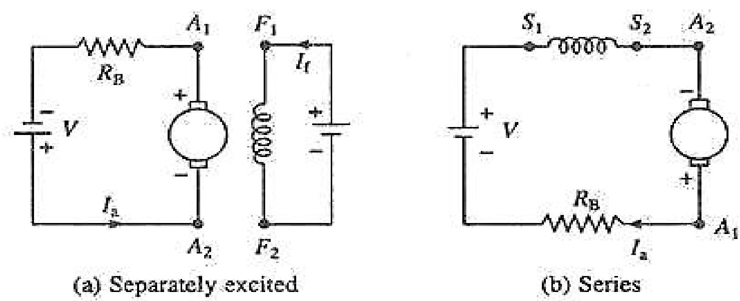


Figure 2-9. Plugging operation of DC motors

Speed torque curves can be obtained from the same basic equations by replacing $\boldsymbol{E_a}$ with $-\boldsymbol{E_a}$ and are shown in the figure 2-10.

Plugging is highly inefficient because in addition to the generated power additional power from a supply source is also wasted in the Braking resistance.

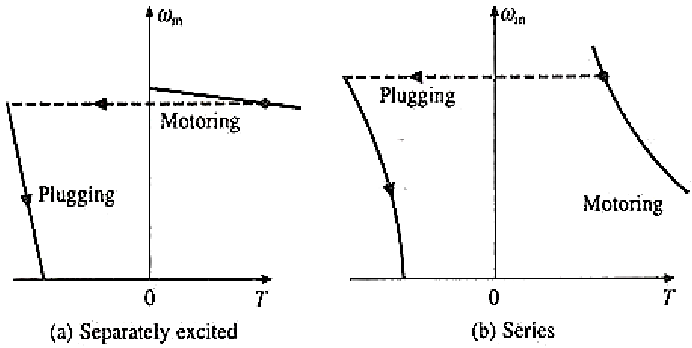


Figure 2-10. Torque speed Characteristics of DC motors during Plugging

2.5.1. Key Characteristics and Considerations:

- **Fast Braking:** Plugging is known for providing very fast braking action, making it suitable for applications where rapid stopping or reversal is critical.
- **High Energy Dissipation:** A significant drawback of plugging is that it dissipates a large amount of energy as heat in the motor windings and any external braking resistors. This makes it less energy-efficient compared to other braking methods like regenerative braking.
- **Stress on Motor and Controller:** The high currents and rapid reversal of torque can put considerable mechanical and electrical stress on the motor, its windings, and the control circuitry. Proper design and protection are crucial.
- **Zero Speed Disconnection:** If the goal is to simply stop the motor, the supply must be disconnected as soon as the motor reaches or approaches zero speed. If not, the motor will accelerate in the reverse direction. Centrifugal switches or other control mechanisms are often used for this purpose.
- **Applications:** Plugging is commonly used in applications requiring quick stops or frequent reversals, such as:
  - Cranes and hoists
  - Elevators

- Rolling mills
- Printing presses
- Machine tools
- Emergency braking systems

2.5.2. Safety and Design Implications:

Due to the high currents and stresses involved, safety is paramount when implementing plugging in electrical drives.

- **Current Limiting:** External resistors are often used to limit the armature current during plugging, protecting the motor and power supply.
- **Overload Protection:** The motor and its associated control system must be adequately protected against overcurrent's and overheating that can occur during plugging.
- **Mechanical Integrity:** The mechanical components of the drive system must be robust enough to withstand the sudden and high braking torques.
- **Control System:** A sophisticated control system is needed to precisely manage the plugging process, ensuring the motor is disconnected at the appropriate time if only stopping is desired.

2.6. Four quadrant operations of DC Motors using a Single fully controlled converter:

As studied earlier, a fully controlled converter can provide a reversible output voltage but current in only one direction. In terms of conventional Voltage-Current diagram shown in the figure below it can work in quadrants 1 and 4 .

A converter can be used say in the first quadrant for motoring operation alone in one direction (and in the third quadrant for motoring operation in other direction) during steady state conditions. But during transient requirements such as starting and breaking it cannot operate in second (or fourth) quadrant where it is required to extract energy from the load for quick braking. (For faster system response))

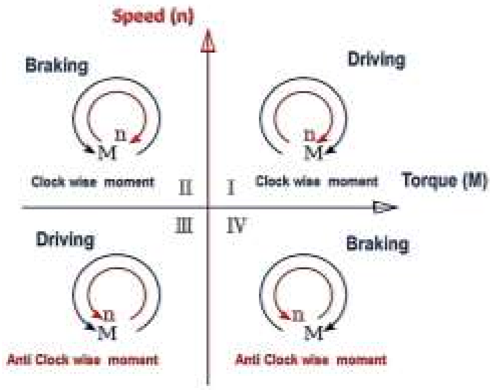


Figure 2-11. Voltage-Current Diagram

If four quadrant operation of a motor is required i.e., reversible rotation and reversible torque in the Torque Speed Plane as shown in the figure below, a single converter along

with changeover contactors to reverse the armature or field connections along with firing angle changeover control [$(0° \leq \alpha \leq 90°)$ *or* $(90° \leq \alpha \leq 180°)$] can be used so as to change the relationship between the converter voltage and the direction of rotation of the motor. (As explained in the introduction to Regenerative braking). Though they are practicable in suitable circumstances, a better performance can be achieved by going in for a Dual Converter.

2.7. Four quadrant operation of DC Motors using Dual Converters:

A dual converter as shown in the figure below consists of two fully controlled converters connected in anti-parallel configuration across the same motor armature terminals. Since both voltage and current of either polarity can be obtained with a dual converter, it can support four quadrant operation of DC motors. Inductors are used to limit the circulating current when both converters are used simultaneously.

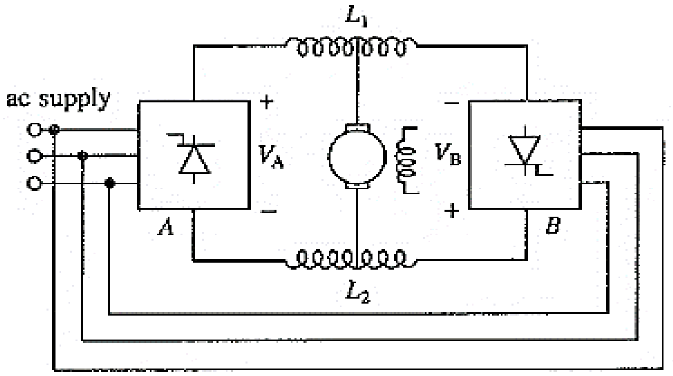


Figure 2-12. Dual converter control of DC separately excited motor. A and B are fully controlled rectifiers. Inductor L_1 and L_2 are used only with simultaneous control (firing angle control $\alpha_A + \alpha_B = 180^0$)

For lower power ratings i.e., up to 10 Kw, single phase Full converters are used and for higher ratings three phase Full converters are used. Typical configuration of both Single phase and three phase Dual converters are shown in the figures 2-13 & 2-14.

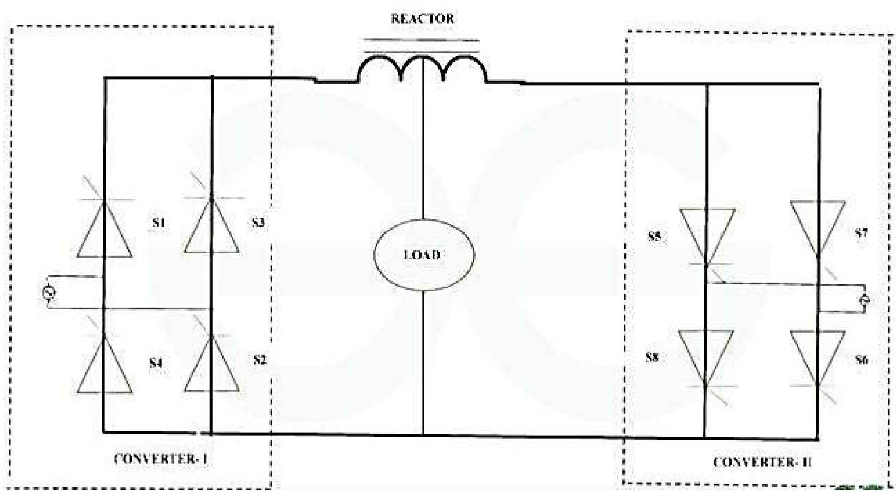


Figure 2-13. Single phase converted as dual converter

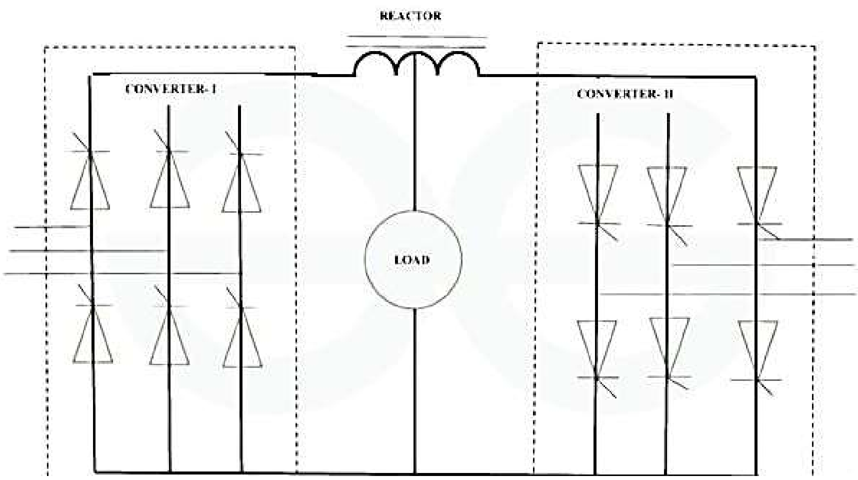


Figure 2-14. Three Phase Converters connected as Dual converters.

In a dual converter the converters are configured such that converter-A works in quadrants 1 and 4 and converter-B works in quadrants 2 and 3.

The operation of Dual converter is first explained with the help of an Ideal dual converter (same figure as shown above but without reactors) with the following assumptions:

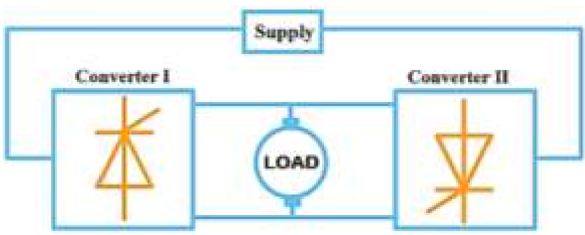


Figure 2-15. Simplified diagram of an Ideal Dual Converter

- They produce pure DC output voltage without any ac ripple.
- Each two-quadrant converter is a controllable DC voltage source with unidirectional current flow. But the current through the load can flow in either direction.
- The firing angle of the converters is controlled by a control voltage $\mathbf{E_C}$

such that their DC output voltages are equal in magnitude but opposite in polarity. So, they can drive current through the load in opposite directions as per requirement.

- Thus, when one converter is operating as a Rectifier and is giving a particular DC output voltage, the other converter operates as an inverter and gives the same voltage at the motor terminals.
- The average DC output voltages are given by:

$$E_{DCA} = E_{max} \cos \alpha_A \ \ and$$
$$E_{DCB} = E_{max} \cos \alpha_B$$

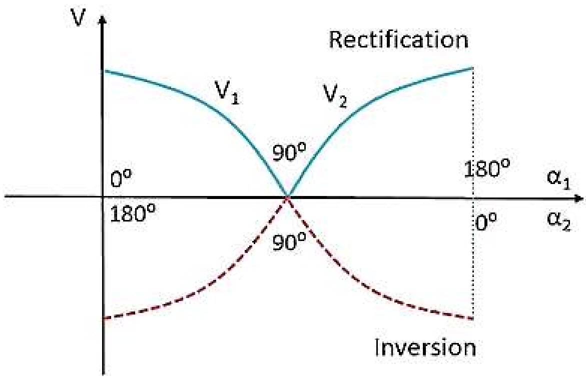


Figure 2-16. Firing angle versus Terminal voltage in Dual converter

In an Ideal converter

$$\boldsymbol{E_{DC} = E_{DCA} = -E_{DCB}}$$

and substituting the above values of $\mathbf{E_{DCA}}$ and $\mathbf{E_{DCB}}$ in this equation we get

$$E_{max} \cos \alpha_A = -E_{max} \cos \alpha_B \text{ or}$$
$$\cos \alpha_A = -\cos \alpha_B$$
$$= \cos(180° - -\alpha_B) \text{ or}$$
$$\alpha_A = 180° - \alpha_B \ or\ (\alpha_A + \alpha_B) = 180°$$

The terminal voltages as a function of the firing angle for the two converters are shown in the figure below. A firing angle control circuit has to see that as the control voltage $\mathbf{E_c}$ changes the firing angles, $\boldsymbol{\alpha_A}$ and $\boldsymbol{\alpha_B}$ are to satisfy the above relation i.e. $(\alpha_A + \alpha_B) = 180°$

2.8. Practical Dual Converters:

In the above explanation of the Dual Converter, it is assumed that when the firing angle is controlled as per the above equation the output voltage is a pure DC voltage without any AC ripple. But in practical dual converters there will be AC ripple and hence the instantaneous voltages from the two converters will be different resulting in circulating current *which will not flow through the load.* If these are not limited, they will damage the converters. Hence in order to avoid/limit such circulating currents two methods are adopted.

Method 1: Dual Converter without circulating current (or non-Simultaneous control): The block diagram of a Dual converter operating in this mode is shown in the figure 2-17.

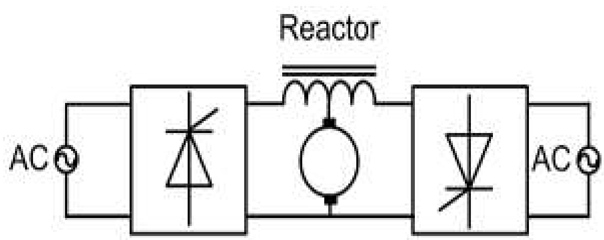


Figure 2-17. Block diagram of a Dual Converter without circulating current

In this mode the flow of circulating current is totally inhibited by controlling the firing Pulses such that only one converter which is required to conduct the load current is active at a time. The other converter is kept inactive by blocking its firing pulses. Since only one converter is operating and the other one is in blocking state, no reactor is required.

Suppose converter-A is operating supplying the load current in a given direction and the converter-B is blocked. If now direction is required to be changed, it is done in the following sequence.

- Load current is first reduced to zero by setting the firing angle of Converter- A to the maximum value (α_A = 90^0.with this firing angle, the converter output voltage and thus output current become zero gradually)
- The pulses to converter-A are withdrawn after confirming that the current through the load due to converter-A has completely come to zero by continuous current sensing.
- Now converter-B is made operational by applying the firing pulses and it would build up the current through the load in the other direction. The pulses to Converter-B are applied only after a further gap of a few milli seconds to ensure reliable commutation of converter-A. For converter B also initially the firing angle α_A is set to 90^0 before applying the firing pulses and then gradually it is brought to 0^0 so that the current builds up take place gradually.

The dead time and hence the reversal time can be reduced by going for accurate zero current sensing methods. When this is done non-simultaneous control provides faster response than simultaneous control. Because of these advantages non-simultaneous control is more widely used.

In this method at certain load conditions the load current may not be continuous which is not a desirable operating condition. To avoid this second method is used.

Method 2: Dual converter with circulating current:

In this mode Current limiting reactors are introduced between the DC terminals of the two converters as shown in the figure to allow the flow of circulating current due to the AC ripple/unequal voltages.

Just like in an Ideal Dual converter the firing angles are adjusted such that

$$(\alpha_A + \alpha_B) = 180°$$

When operating in quadrant 1 Converter-A will be working as a rectifier ($0^0 \leq \alpha \leq 90^0$) and converter-B will be working as an Inverter. ($90^0 \leq \alpha \leq 180^0$) For e.g. firing angle of converter A is say 60°, then the firing angle of converter B will be 120°**.** With these firing angles, Converter A will be working as a converter and converter B will be working as an inverter. So, in circulating current mode both converters will be operating. The operation of the converters is to be interchanged for speed reversal i.e. converter1 which was working as a converter should now work as an Inverter and converter 2 which was working as an Inverter should now work as a converter. Two separate firing circuits have to be used for the two converters.

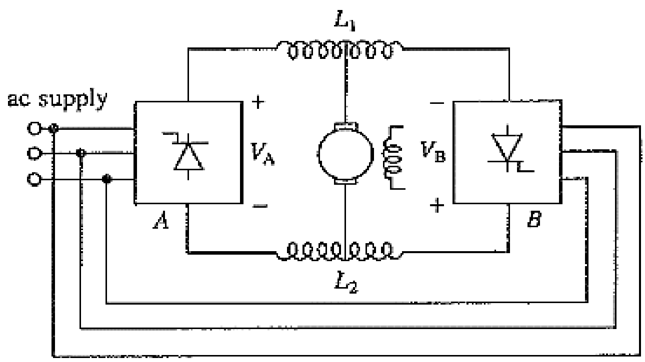


Figure 2-18. Dual Converter Control of a DC separately excited motor in simultaneous or circulating current mode

But for speed reversal α_A is to be increased gradually towards 180^0 and α_B is to be decreased gradually towards 0^0 while simultaneously satisfying the above condition (1)

In this process, the armature current reduces to zero, reverses direction, shifts to Converter B and the motor will now operate initially in quadrant 2 during braking and then in quadrant 3 during acceleration and finally at the required steady state speed. The current loop adjusts the firing angle α_B continuously so as to break the motor at the maximum allowable current from initial speed to zero speed and then accelerates to the desired speed in the opposite direction. As α_B is changed α_A is also changed continuously so as to maintain the above relation-1. During this entire operation, the closed loop control system will ensure the smooth transfer from quadrant 1 to quadrant 2 to quadrant 3.

2.8.1. Advantages and Disadvantages of the Circulating current mode of Dual Converters:

2.8.1.1. Advantages of Circulating Current Mode:

- **Smooth Reversal of Load Current:** This is a major benefit. Because both converters are continuously in conduction (one acting as a rectifier and the other as an inverter), the current reversal is smooth and continuous, without the need for a "dead time" (a brief period where neither converter is active) as required in non-circulating current mode. This is crucial for applications requiring frequent and rapid current direction changes.
- **Improved Speed of Response:** The continuous conduction allows for faster dynamic response to changes in load or control signals. There's no delay in waiting for one converter to turn off and the other to turn on, leading to better control and quicker changes in motor speed and direction in drive applications.
- **Continuous Conduction of Converters:** Both converters remain in conduction regardless of the load, even at no-load conditions. This helps in maintaining stable operation and voltage regulation.
- **Four-Quadrant Operation:** Circulating current dual converters inherently support four-quadrant operation, meaning they can handle forward motoring, forward braking (regeneration), reverse motoring, and reverse braking. This makes them highly versatile for reversible DC drives.

2.8.1.2. Disadvantages of Circulating Current Mode:

- **Requirement of a Circulating Current Reactor:** To limit the magnitude of the circulating current that flows between the two converter bridges (due to the instantaneous voltage difference between them, even if their average voltages are equal), a series inductor (reactor) is absolutely necessary. This reactor adds to the size, weight, and cost of the overall system.

- **Increased Losses and Lower Efficiency:** The circulating current, while controlled by the reactor, still flows through the converter components (thyristors, etc.). This extra current contributes to power losses (I^2R losses) in the converters and the reactor itself, leading to reduced overall efficiency.
- **Lower Power Factor:** The circulating current can negatively impact the input power factor of the system.
- **Higher Current Ratings for Thyristors:** Since the thyristors in both converters have to handle both the load current and the circulating current, they need to be rated for higher currents than if they were only handling the load current. This increases the cost and size of the power semiconductors.
- **More Complex Control:** While offering benefits in response, the control circuitry for circulating current mode is generally more complex than for non-circulating current mode because it needs to manage the firing angles of both converters simultaneously to ensure stable operation and limit the circulating current.

while the circulating current mode offers significant advantages in terms of dynamic response and smooth current reversal, particularly for demanding applications like reversible DC motor drives, these come at the cost of increased complexity, larger components (due to the reactor), higher losses, and reduced efficiency and power factor. The choice between circulating and non-circulating current modes depends heavily on the specific application requirements, especially regarding dynamic performance and cost considerations.

2.8.2. Comparison between Circulating current mode and non-circulating current mode Dual converters:

Dual converters are power electronic circuits that allow for bidirectional power flow and four-quadrant operation, meaning they can control both the direction of current and voltage, enabling applications like reversible DC motor drives. They achieve this by connecting two controlled converters (typically full bridge rectifiers) in an anti-parallel arrangement to a common DC load.

There are two primary modes of operation for dual converters:

2.8.2.1. Non-Circulating Current Mode (Circulating Current Free Mode)

In this mode, only one converter operates at a time to supply current to the load. The other converter is completely blocked by not applying firing pulses to its thyristors.

How it works:

- When a change in load current direction or voltage polarity is required, the conducting converter is first turned off, allowing its current to decay to zero.
- After a small but necessary "dead time" (typically 10-20 ms) to ensure all SCRs in the first converter are fully turned off, the second converter is then triggered to take over. This delay prevents a short circuit between the two converters.
- If converter 1 is operating as a rectifier ($0° < \alpha 1 < 90°$), Vdc and Idc are positive.
- If converter 2 is operating as a rectifier ($0° < \alpha 2 < 90°$), Vdc and Idc are negative.

Advantages:

- **No circulating current:** This is the main advantage, as it eliminates the need for a circulating current limiting reactor, reducing circuit complexity, size, cost, and power losses.
- **Higher efficiency:** Due to the absence of circulating current losses.
- **Better power factor:** Generally better as there are no additional reactive

components for current limiting.

Disadvantages:

- **Slower response time:** The "dead time" or blanking time required for the current to decay to zero in the outgoing converter and for it to turn off safely introduces a delay in the reversal of load current or voltage polarity. This makes it unsuitable for applications requiring very fast dynamic response.
- **Not suitable for continuous conduction at low loads:** At light or no-load conditions, the current may become discontinuous, making control more challenging.
- **Abrupt changes:** The switching between converters can lead to abrupt changes in voltage or current, which might not be desirable for certain sensitive loads.

2.8.3. Circulating Current Mode

In this mode, both converters are gated simultaneously, but with their firing angles adjusted such that their average output voltages are equal in magnitude but opposite in polarity. This condition typically means that if $\alpha 1$ is the firing angle for converter 1 and $\alpha 2$ for converter 2, then $\alpha 1+\alpha 2=180°$. One converter act as a rectifier, and the other acts as an inverter.

How it works:

- Even though the average output voltages are equal and opposite, there is an instantaneous voltage difference between the two converters due to ripples in their output. This instantaneous voltage difference drives a "circulating current" between the two converters.
- To limit this circulating current to a safe value, a circulating current limiting inductor (reactor) is connected between the output terminals of the two converters. This inductor absorbs the instantaneous voltage

difference.

- If converter 1 is a rectifier (0° < α1 < 90°), then converter 2 acts as an inverter (90° < α2 < 180°), leading to positive Vdc and Idc.
- If converter 1 is an inverter (90° < α1 < 180°), then converter 2 acts as a rectifier (0° < α2 < 90°), leading to negative Vdc and Idc.

Advantages:

- **Faster dynamic response:** The continuous conduction of both converters (due to the circulating current) eliminates the dead time required for current decay, allowing for smooth and rapid reversal of load current and voltage. This makes it ideal for applications requiring fast changes in operating quadrants, like high-performance motor drives.
- **Smooth current reversal:** The presence of circulating current ensures continuous conduction, leading to smoother transitions in load current.
- **Better waveform quality:** The output voltage waveforms are generally better defined due to continuous conduction.

Disadvantages:

- **Requires a circulating current limiting reactor:** This adds to the cost, size, and weight of the system.
- **Increased losses:** The circulating current flows continuously through both converters and the reactor, leading to additional power losses and reduced efficiency.
- **Higher SCR ratings:** The thyristors in both converters must be rated for the sum of the load current and the circulating current, increasing their current handling requirements and thus their cost.
- **Lower power factor:** The presence of the reactor and circulating current can sometimes lead to a slightly lower overall power factor compared to the non-circulating mode.

Table 2-1. Circulating current Mode Vs Non circulating current mode

Feature	Circulating Current Mode	Non-Circulating Current Mode
Operation	Both converters operate simultaneously.	Only one converter operates at a time.
Circulating Current	Present (limited by a reactor).	Absent (actively prevented by blocking one converter).
Response Speed	Fast, smooth reversal of current/voltage.	Slower, due to dead time.
Current Reversal	Smooth.	Abrupt, with a dead time.
Reactor Requirement	Yes, required for current limiting.	No, not required.
Efficiency	Lower, due to circulating current losses.	Higher, no circulating current losses.
SCR Current Rating	Higher (handle load current + circulating current).	Lower (handle only load current).
Complexity	More complex due to circulating current control.	Simpler control.
Cost	Higher (due to reactor and higher-rated SCRs).	Lower.
Applications	High-performance drives, frequent reversals.	General-purpose drives, less frequent reversals.

2.9. Closed loop control of Drives:

Closed loop control in Electrical drives is provided mainly to meet any or all of the following requirements.

- Protection against over current and over voltages
- Enhancement of Speed of response (Transient performance)
- Improve the steady state accuracy

We will study two important schemes of control that are most commonly used in electrical Drive control systems.

2.10. Current Limit Control:

Basic block diagram of a typical current limit control employed in electrical drives is shown in the figure 2-19.

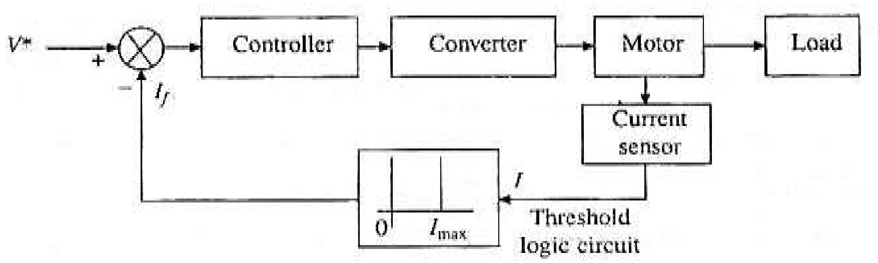


Figure 2-19. Current limit Control

This is employed mainly to limit the converter and motor currents to safe values during transient periods like starting and braking. It employs a current feedback loop with a threshold logic circuit. The motor current is sensed using sensors like CTs or Hall Effect sensors and fed to the threshold logic circuit. As long as the motor current is within the set maximum limit, the closed loop control does not come into operation. When the current exceeds the set limit the closed loop control becomes active and the current is brought below the set limit and the control loop becomes again inactive. Whenever current exceeds the limit the control loop becomes active again. Thus, the current fluctuates around the maximum limit until the final steady state condition is reached thus ensuring faster response with maximum torque during the transient conditions i.e., starting and braking.

2.11. Closed loop Speed control:

The most widely used control loop in electrical drives is the "*closed loop Speed control*" and its Block schematic is shown in the figure below. It employs an inner current control loop within an outer speed control loop. Inner current control loop is provided to limit the converter and motor current (torque) below the safe limits. The speed control loop operates as follows:

ω^*_m is the input speed reference and when it increases (or decreases) it produces a positive (or negative) speed error (+/-) $\Delta\omega_m$. The speed error is processed through a speed controller and is applied to the current loop as current reference I* through the current limiter. Current limiter works linearly in a small range of error and saturates when the error exceeds the set limits.

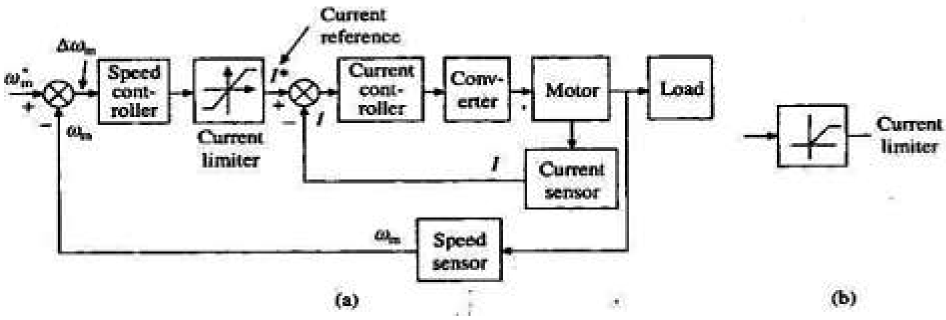


Figure 2-20. Closed loop speed control

An increase in the speed reference ω^*_m produces a positive speed error and the current limiter sets a positive maximum allowable input current as reference to the inner current loop. Now the motor accelerates at the maximum current and hence with the maximum torque until it approaches the set speed. When it is close to the set speed, the current limiter desaturates and the speed stabilizes at the steady state value of speed with a small steady state error and a current corresponding to the motor torque equal to the load torque.

A decrease in the speed reference ω^*_m produces a negative speed error and the current limiter sets a negative maximum allowable input current as reference to the inner current loop. Now the motor decelerates and operates in braking mode at the maximum current and hence with the maximum torque until it approaches the set speed. When it is close to the set speed, the current limiter desaturates and the speed stabilizes at the steady state value of speed with a small steady state error and a current corresponding to the motor torque equal to the load torque.

In drives where there is no provision for current to reverse (single quadrant operation) for braking operation current limiter will have the unipolar I/O characteristics as shown in fig (b). In drive systems where there is enough load torque for braking, electric braking is not required and, in such cases, also the unipolar current limiter will be used.

Current and speed controllers shown in the speed control loop normally consist of PI (Proportional plus Integral) or PD (Proportional plus Derivative) or PID (Proportional plus Integral plus derivative) controllers depending upon the steady-state accuracy and/or transient response requirements.

Summary:

Important concepts and conclusions:

- An electrical drive operates in three modes. i.e., steady state, starting and braking.
- Steady state operation is also referred to as motoring operation.
- Starting and braking are also referred to as transient operations.
- The three types of electrical braking are:
    - Regenerative braking
    - Dynamic or Rheostatic Braking and
    - Plugging or reverse voltage braking.
- Four quadrant operation can be achieved with a single Full converter along with changeover contactors to reverse the armature or field connections and with firing angle changeover control [($0° \leq \alpha \leq 90°$) or ($90° \leq \alpha \leq 180°$)]. But Dual converters are preferred due to their superior performance.
- In practical Dual converters with circulating current mode, reactors are required to be connected between the two Converter terminals to limit the circulating currents. The firing angles are to be controlled to satisfy the condition $(\alpha_A + \alpha_B) = 180°$
- In converters without circulating current only one converter is active at a

given time depending on the operation.

- In both modes the closed loop control system takes care of the total control methodology.
- In closed loop speed control systems normally two control loops are used. An inner Current control loop and an outer Speed control loop.
- Current and Speed controllers in a closed loop speed control system normally consist of PI (Proportional plus Integral) or PD (Proportional plus Derivative) or PID (Proportional plus Integral plus derivative) controllers depending upon the steady-state accuracy and/or transient response requirements.

Example 2-1:

A 210 V, 1200 RPM, 10 A separately excited DC motor is controlled by a 1-phase fully controlled converter with an AC source voltage of 230V, 50 Hz. Assume that sufficient inductance is present in the armature circuit to make the motor current continuous and ripple free for any torque greater than 25% of rated torque. $R_a = 1.5\ \Omega$

a) What should be the value of the firing angle to get the rated torque at 800 rpm?

b) Compute the firing angle for the rated braking torque at -1200 rpm.

c) Calculate the motor-speed at the rated torque and $\alpha = 165^0$ for the regenerative braking in the second quadrant?

Solution:

This is an example where the constant K_a is not given directly and no mention is made about field current. So, we can assume field Ø as constant and determine the motor constant $K_a Ø$ from the given rated values of voltage (210 V), speed (1200 rpm), armature current (10 A) and the armature resistance (1.5 Ω)

First, we have to find out back emf E_b @rated conditions and from that the constant $K_a Ø$.

$E_b = E_a - I_a R_a = 210 - (10 \times 1.5) = 195\,V$

Rated speed in R/s: $\omega = \frac{1200 \times 2\pi}{60} = 125.66.\,rad/sec$

We know that $E_b = K_a\,Ø\omega$ from which we have:

$K_a Ø = \frac{E_b}{\omega} = \frac{195}{125.66} = 1.55\frac{V}{rad}/sec$

Now we can find out the required quantities one by one.

a) **At rated torque, I_a = 10 A.**

Back $e.m.f.$ at 800 rpm = $E_{b1} = \frac{800}{1200} = 130\,V$

We know that with continuous conduction required armature voltage $E_a(\alpha)$ from the single-phase full converter is given by:

$E_a\alpha = \frac{2E_m}{\pi} cos\alpha = I_a R_a + E_b \quad (E_m = 230 \times \sqrt{2} = 325.27V)$

$E_a\alpha = \frac{2\times 325.27}{\pi} cos\alpha = (10 \times 1.5) + 130$

From which we get $\alpha = 45.55^0$

b) For the speed of – 1200 rpm at the rated current $E_b = -195\,V$ and the armature loop equation becomes $\frac{2\times 325.27}{\pi} cos\alpha = (10\times 1.5) - 195$ from which α 150.37^0 (b) Substituting the value of armature current I_a at rated torque = $10\,A$ in the armature loop equation and equating it to the converter output at a firing angle of $\alpha = 165^0$, we get

$\frac{2\times 325.27}{\pi} cos165^0 = 10\times 1.5 + E_b \; or \; E_b = -215.02V$

Regenerative braking (second quadrant operation) is obtained either by the field reversal or the armature reversal, for which, $K_a\,Ø = -1.55$

Then, $\omega = \frac{E_b}{K_a Ø} = \frac{-215.02}{-1.55} = 138.72\frac{rad}{s}\, and\; N = \frac{138.72\times 60}{2\pi} = 1325\,rpm$

Example 2-2:

The speed of a 10 HP, 210 V, 1000 rpm separately excited D.C. motor is controlled by a single-phase, full-converter. The rated motor armature current is 30 A, and the armature resistance is $R_a = 0.25\ \Omega$. The a.c. supply voltage is 230 V. The motor voltage constant is $K_a\Phi = 0.172$ V/rpm. Assume that sufficient inductance is present in the armature circuit to make the motor current continuous and ripple free.

a) Rectifier operation (motoring action): For a firing angle of $\alpha = 45^0$, and rated motor armature current, determine: Motor torque and Motor speed
b) Inverter operation (regenerative action): The motor back emf polarity is reversed by reversing the field excitation. Determine: Firing angle to keep the motor current at its rated value and Power fed back to the supply

Solution:

Rectifier operation (motoring action):

Motor Torque @rated armature current: can be found out directly by using the relation $T = K_a \Phi I_a$. But the constant $K_a \Phi$ is same in the relations for torque and back emf if it is V/Rad/sec in back emf and N-m/A in torque. But it is given in V/RPM. Hence it is first converted to V/Rad/sec and then used in the expression for torque.

$$K_a\ \Phi\ (V/Rad/sec) = K_a\ \Phi\ (V/RPM)\ x\ 60/2\pi$$

$$K_a\ \Phi = \frac{0.172\times 60}{2\pi} V - \frac{s}{rad} = 1.64V - s/rad$$

Rated Motor Torque T_R at rated armature current

$$= K_a \Phi I_a R = 1.64 \times 30 = 49.2\ N - m.$$

Motor Speed at Rated armature current: The armature voltage in a fully controlled single-phase converter is given by:

$$E_A = \frac{2E_m}{\pi} cos\alpha = \frac{2\sqrt{2}\times 230}{\pi} cos45^0 = 146.42$$

(The given supply voltage of 230 V is RMS value and it is to be converted into

E_m by multiplying by √ 2)

$E_b = E_a - I_{aR}R_a = 146.42 - (30 \times 0.25) = 138.92V$

Speed, $N = \frac{E_b}{K_a\emptyset} = \frac{138.92}{0.172} = 807.67\ rpm$ (here K Φ is used directly with given units of V/RPM so that we can get directly speed N in RPM)

Inverter operation (regenerative action):

- *Firing angle to keep the motor current at its rated value:*

At the time of polarity reversal, the back emf is $E_b = 138.92\ V$
(But it is to be taken as negative after polarity reversal for braking)

Then from loop equation

$$E_a = E_b + I_a R_a = -138.92 + (30 \times 0.25) = -131.42\ V.$$

But converter out is given by $E_a = \frac{2\sqrt{2}\times 230}{\pi} cos\alpha = -131.42V$

Equating the converter output voltage to the required motor armature voltage, we get $\alpha = 129.39^0$

- *Power fed back to the supply:*

Power from the D.C machine is: $P_g = 138.92 \times 30 = 4167.6$

Power lost in the armature resistance is: $P_L = Ia^2\ R_a = 30^2 \times 0.25$

Power fed back to the A.C. supply is: $P_s = 4167.6 - 225 = 3942.6\ W$

We can get directly also power fed back as: $P_s = E_a\, I_a = 131.42 \times 30 = 3942.6\ W.$

Chapter-3.

Control of DC motors by Choppers

3.1. Introduction to Choppers:

A chopper (also known as a DC-DC converter) is a fundamental power electronic device that plays a crucial role in controlling DC power. Essentially, it acts as a high-speed electronic switch that converts a fixed DC input voltage into a variable DC output voltage.

Imagine you have a battery (a fixed DC voltage source) and you want to power a DC motor, but you need to control its speed. Simply connecting the motor directly to the battery would give you a fixed speed. This is where a chopper comes in. By rapidly turning the DC supply on and off to the motor, the chopper effectively "chops" the continuous DC voltage into a series of pulses. The average value of this pulsed voltage can then be controlled, which in turn controls the motor's speed.

3.1.1. Key Characteristics and Operating Principle:

- **DC to Variable DC Conversion:** The primary function of a chopper is to transform a constant DC voltage into a controlled or adjustable DC voltage. This is achieved without converting it to AC first, making it highly efficient.

- **High-Speed Switching:** Choppers employ power semiconductor devices (like MOSFETs, IGBTs, GTOs, or power BJTs) that can switch ON and OFF at very high frequencies (typically in kilohertz to megahertz range).
- **Pulse Width Modulation (PWM):** The most common control technique for choppers is Pulse Width Modulation (PWM). In PWM, the frequency of the switching is kept constant, but the duration for which the switch is ON (the "ON time," TON) within a fixed total time period (T) is varied. The ratio of TON to T is called the **duty cycle (α)**, and the average output voltage is directly proportional to this duty cycle ($V_{out}=\alpha \cdot V_{in}$). By changing the duty cycle, the average output voltage can be precisely controlled.
- **Energy Transfer and Storage:** In many chopper circuits, an inductor is used to store energy during the ON period and release it during the OFF period, helping to smooth the output current and voltage. A freewheeling diode is often included across the inductive load to provide a path for the current when the chopper switch is OFF, preventing large voltage spikes.

3.1.2. Why are Choppers Important in Electrical Drives?

- **Speed Control of DC Motors:** This is one of the most significant applications. Choppers provide smooth, efficient, and precise control over the armature voltage (and thus speed) of DC motors in various applications like electric vehicles, industrial machinery, and traction systems.
- **Regenerative Braking:** Choppers can facilitate regenerative braking, where the motor acts as a generator during braking, feeding energy back to the supply (e.g., battery in an electric vehicle), improving efficiency.
- **High Efficiency:** Due to their switching nature, choppers have very low power losses (as the switching device is either fully ON or fully OFF, minimizing resistive losses), leading to high efficiency (often up to 95%).
- **Compact Size and Fast Response:** Their high switching frequencies

allow for smaller reactive components (inductors and capacitors), leading to compact designs and fast dynamic response.

- **No Power Factor Issues:** When supplied from a DC source (like batteries), choppers do not introduce power factor problems, unlike AC-DC phase-controlled converters.

Choppers are mainly used to obtain a variable DC output voltage from Fixed DC voltage source. There are two basic types of choppers: AC link choppers and DC choppers.

- **AC link Choppers:** In these, first DC is converted to AC by inverters. Then AC is stepped up or down by transformers to the required level and then it is converted back to DC.
- **DC choppers:** In these a variable DC voltage is obtained from a fixed DC voltage using a static switch.

In this unit we will study the application of DC choppers in the four-quadrant operation of DC motors.

3.2. Basic DC chopper classification:

- According to the level of input/output voltages:
  - **Step down choppers:** Output voltage is lesser than the input voltage
  - **Step up choppers:** Output voltage is larger than the Input voltage
- According to the Direction of output voltage and current as shown in the
- Figure below (as class A to E)
- According to quadrants of operation: (As shown in the figure 3.1.)

One quadrant chopper: The output voltage and current are both positive.
(Class- A): The output voltage is positive but current is negative.
(Class- B): Two quadrant chopper:
The output voltage is positive but current can be positive or negative.
(Class-C): The output current is positive but voltage can be positive or negative.

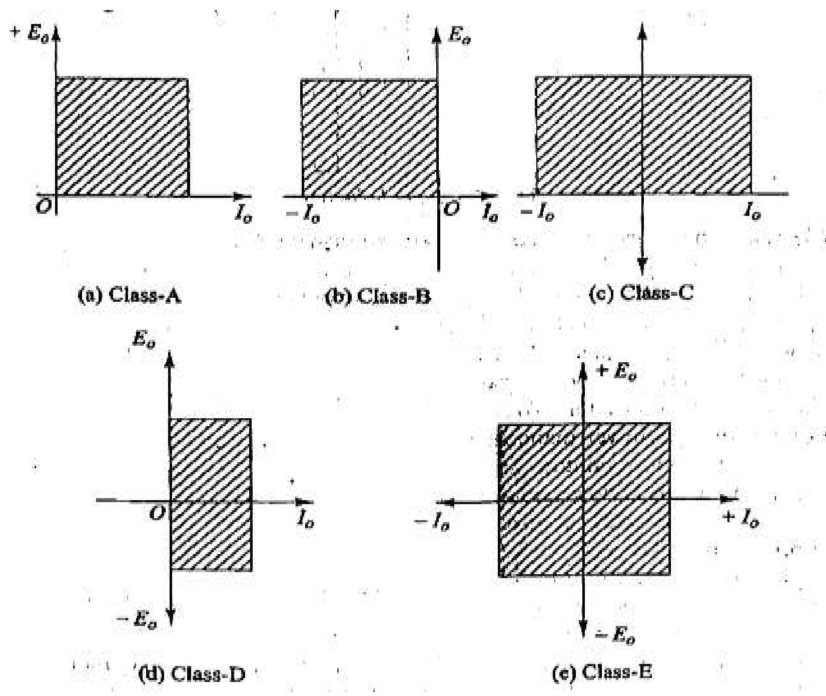


Figure 3-1. Classification of DC choppers

Four quadrant choppers: The output voltage and current both can be positive or negative.

3.3. Basic principle of operation of a step-down chopper:

A step-down chopper consists of a semiconductor device like SCR, BJT, Power MOSFET, IGBT, GTO etc. which works like switch along with a DC input source and other components like Inductors, Resistors, Capacitors, Diodes etc. as shown in the figure below. The average output voltage across the load is varied by varying the **ON** period (duty cycle) of the chopper with a given Time period.

For SCR based choppers an additional commutation circuit is necessary. Hence in general, gate commutation devices like MOSFETs and IGBTs have replaced the SCRs in Choppers. However, for high voltage and high current applications SCRs are still used.

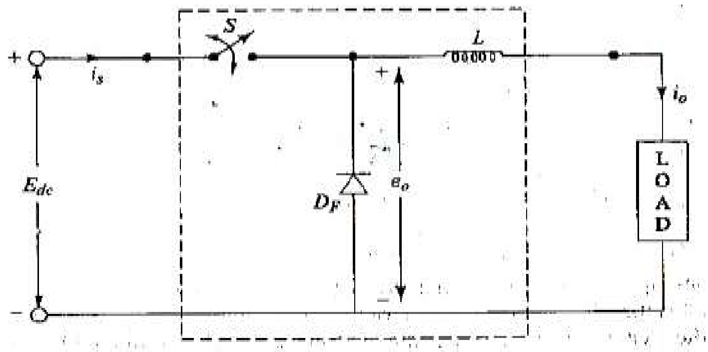


Figure 3-2. Basic Chopper circuit

The power diode D_F operates in freewheeling mode and provides a path to the load current when the switch is not ON. The Inductor works as a filter and smoothes out the switching ripple. The chopped output voltage waveform and the load current are shown in the figure 3-3.

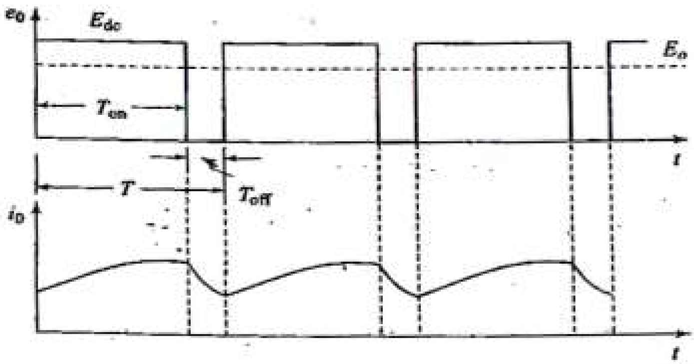


Figure 3-3. DC Chopper output voltage and current waveforms

During the *ON* period of the chopper the input voltage gets applied to the load. During the *OFF* period the load gets short circuited by the freewheeling Diode D_F and the load current flows through D_F. Thus, a chopped voltage is produced across the load. *This is also called Time Ratio control.*

The average output voltage is given by:

$$E_0 = \frac{E_{DC}.T_{ON}}{T_{OFF} + T_{ON}} = \frac{E_{DC}T_{ON}}{T}$$

Where $T_{ON} = ON$ period of the chopper

$T_{OFF} = OFF$ period of the chopper and

$\mathrm{T} = \mathrm{T_{OFF}} + \mathrm{T_{ON}}$ = Chopping period.

$\frac{T_{ON}}{T}$ is called *duty ratio* of the chopper and is represented by the symbol **δ**.

Then the output voltage E_O is given by**:**

$E_O = \delta . E_{DC}$

The output voltage E_O is also given by: $\mathrm{E_O = E_{DC}. T_{ON}. f}$

where f is the chopping frequency and is equal to $\frac{1}{T}$

The average value of the load current is given by:

$$I_O = \frac{E_O}{R} = \delta . \frac{E_{DC}}{R}$$

Types of chopper control:

If the chopper is Transistor based, the base current will switch ON and OFF the transistor.

- If it is GTO thyristor based then a positive gate pulse will switch it ON and a negative gate pulse will switch it OFF
- If it is SCR based a commutation circuit is required to turn it OFF.

3.3.1. Class-A Chopper (First Quadrant operation):

A Class-A Chopper, also known as *a First Quadrant Chopper* or *Type-A Chopper,* is a fundamental DC-DC converter that operates exclusively in the first quadrant of the output voltage (Vo) vs. output current (Io) plane. This means that both the average output voltage and average output current are always positive.

3.3.1.1. Key Characteristics:

- **Unidirectional Power Flow:** Power always flows from the source to the load. It acts as a step-down converter, meaning the average output voltage is always less than or equal to the input DC voltage (Vs).
- **Positive Voltage and Current:** Both the output voltage and output

current are always positive. This defines its operation in the first quadrant.

- **Simple Circuitry:** It typically consists of a power semiconductor switch (like a MOSFET, IGBT, or SCR), an inductor, and a freewheeling diode.
- **Control Method:** The output voltage is controlled by varying the "ON" time (TON) of the chopper switch relative to the total switching period (T). This is commonly achieved using Pulse Width Modulation (PWM). The duty cycle (α) is defined as α=TON/T. The average output voltage is given by Vo=α·Vs.

The basic power circuit of a Class-A chopper connected to a separately excited motor operating in the first quadrant is shown in the figure below.

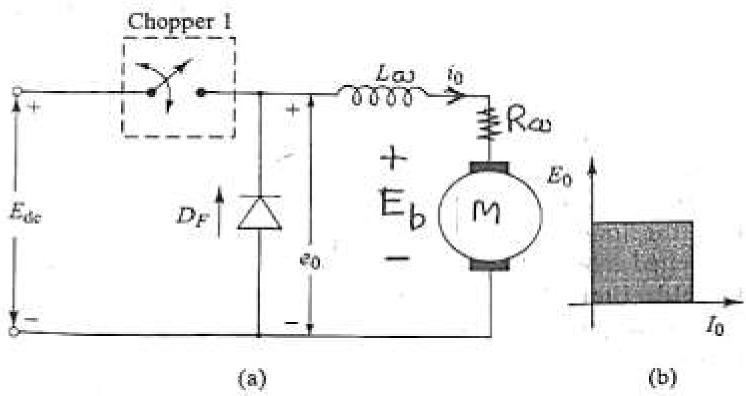


Figure 3-4. First quadrant operation of a Class-A chopper connected to a DC separately Excited motor

The term first quadrant refers to the operation with both voltage E_0 and current I_0 polarities confined to the directions as shown. When the chopper is ON the output voltage $E_O = E_{DC}$ and when the chopper is OFF $E_O = 0$ volts but the current I_O flows in the load in the same direction through the freewheeling diode D_F.

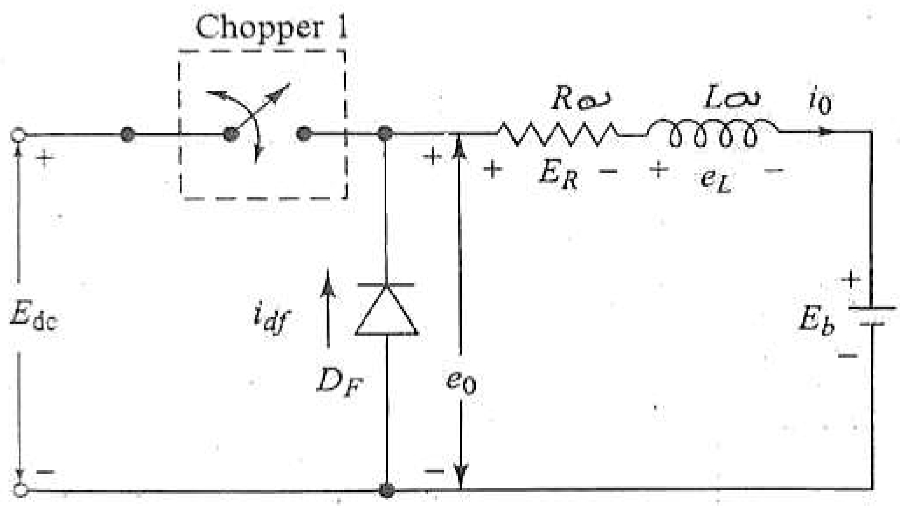


Figure 3-5. Electrical equivalent circuit of Class-A chopper (polarities indicated are when Chopper is ON)

Both average load voltage and load current are positive and hence power flows from source to load. *Hence this is Motoring operation*. The output voltage and current waveforms are shown in the figure 3-6.

- According to the level of input/output voltages:
    - Step down choppers: Output voltage is lesser than the input voltage
    - Step up choppers: Output voltage is larger than the Input voltage
- According to the Direction of output voltage and current as shown in the
- Figure below (as class A to E)
- According to quadrants of operation: (As shown in the figures above)

One quadrant chopper:

- The output voltage and current are both positive. (Class- A)
- The output voltage is positive but current is negative. (Class- B)

Two quadrant choppers:

- The output voltage is positive but current can be positive or negative.

(Class-C)

- The output current is positive but voltage can be positive or negative. (Class-D)

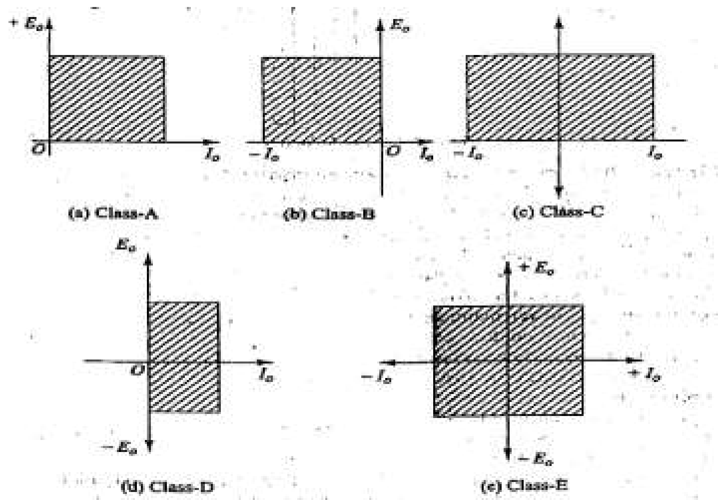


Figure 3-6. Classification of DC choppers

Applications:

Class-A choppers are primarily used in applications where:

- Unidirectional power flow is sufficient.
- The load requires a variable DC voltage that is less than or equal to the source voltage.

Common applications include:

- **Speed control of DC series motors:** By varying the average voltage applied to the motor, its speed can be controlled.
- **Low-power DC motor drives:** For simple motoring operations where regenerative braking or reverse operation is not required.
- **Some types of switched-mode power supplies (SMPS):** As a basic buck converter stage.
- **Battery charging circuits:** To regulate the charging voltage and current.

3.3.2. Four quadrant choppers:

A *four-quadrant chopper*, also known as a *Class-E chopper or H-bridge DC-DC converter*, is a power electronic circuit that can control both the magnitude and polarity of the output voltage and current. This means it can operate in all four quadrants of the voltage-current (V-I) plane.

A four-quadrant chopper typically consists of four semiconductor switches (like IGBTs, MOSFETs, or GTOs) and four anti-parallel diodes arranged in an H-bridge configuration. By strategically switching these devices ON and OFF, the chopper can achieve the desired output voltage and current characteristics.

Let's break down the "four quadrants" of operation:

- **Quadrant I (Forward Motoring):**
  - Output voltage (Vo) is positive, and output current (Io) is positive.
  - Power flows from the source to the load.
  - The chopper acts as a step-down converter, providing a variable positive voltage to the load. This is the typical "motoring" mode where a DC motor rotates in the forward direction.
- **Quadrant II (Forward Braking/Regenerative Braking):**
  - Output voltage (Vo) is positive, but output current (Io) is negative.
  - Power flows from the load back to the source.
  - The chopper acts as a step-up converter. This mode is used for braking, where the kinetic energy of the load (e.g., a motor) is converted back into electrical energy and fed to the source, offering efficient braking and energy recovery.
- **Quadrant III (Reverse Motoring):**
  - Output voltage (Vo) is negative, and output current (Io) is negative.
  - Power flows from the source to the load, but in the opposite direction.
  - The chopper provides a variable negative voltage to the load, causing the motor to rotate in the reverse direction.

- **Quadrant IV (Reverse Braking/Regenerative Braking):**
  - Output voltage (Vo) is negative, but output current (Io) is positive.
  - Power flows from the load back to the source.
  - Similar to Quadrant II, this mode is used for braking, but when the motor is rotating in the reverse direction.

3.3.2.1. Key Features and Advantages:

- **Bidirectional Power Flow:** Can transfer power from source to load and vice versa.
- **Bidirectional Voltage and Current Control:** Allows for precise control over both voltage and current polarity.
- **Versatile Operation:** Capable of motoring and braking in both forward and reverse directions.
- **Smooth Control:** Offers continuous and precise control over the output.
- **Energy Efficiency:** Enables regenerative braking, recovering energy during deceleration, which is highly beneficial in applications like electric vehicles.

3.3.2.2. Applications:

Four-quadrant choppers are widely used in applications requiring precise and flexible DC motor control, including:

- **DC Motor Drives:** This is a primary application, allowing for forward/reverse motoring and braking (regenerative and dynamic) of DC motors in industrial drives, electric vehicles, and traction systems (e.g., electric trains, subway trains).
- **Electric Vehicles (EVs):** Crucial for controlling the traction motor, enabling acceleration, deceleration, and regenerative braking to extend battery range.
- **Renewable Energy Systems:** Used in solar power systems (e.g., for maximum power point tracking) and wind turbines to manage power flow

and convert varying DC voltages.

- **Battery Chargers:** For efficient and controlled charging of battery banks, especially in applications where energy recovery is important.
- **Power Supplies and Voltage Regulators:** To provide regulated DC voltage with variable polarity in some specialized power supply units.

3.3.2.3. Disadvantages (generally in comparison to simpler choppers):

- **Complexity:** They are more complex in terms of circuit design and control algorithms due to the multiple switching devices and the need for coordinated control.
- **Cost:** The increased number of power semiconductor devices and the more intricate control circuitry generally lead to higher manufacturing costs.
- **Losses:** With more switching devices, there can be increased conduction and switching losses, although modern devices and control techniques aim to minimize this.

3.4. Basic principle of operation of a step-down chopper:

A step-down chopper, also known as a *buck converter,* is a type of DC-to-DC converter that reduces a fixed DC input voltage to a lower, controllable DC output voltage. It's a fundamental circuit in power electronics, widely used for efficient voltage regulation.

A step-down chopper consists of a semiconductor device like SCR, BJT, Power MOSFET, IGBT, GTO etc. which works like switch along with a DC input source and other components like Inductors, Resistors, Capacitors, Diodes etc. as shown in the figure below. The average output voltage across the load is varied by varying the **ON** period (duty cycle) of the chopper with a given Time period.

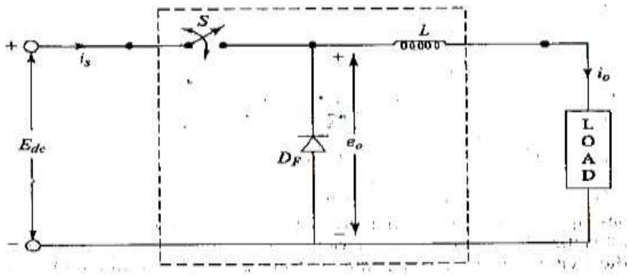


Figure 3-7. Basic Chopper circuit

For SCR based choppers an additional commutation circuit is necessary. Hence in general, gate commutation devices like MOSFETs and IGBTs have replaced the SCRs in Choppers. However, for high voltage and high current applications SCRs are still used. The power diode D_F operates in freewheeling mode and provides a path to the load current when the switch is not **ON.** The Inductor works as a filter and smoothes out the switching ripple. The chopped output voltage waveform and the load current are shown in the figure below.

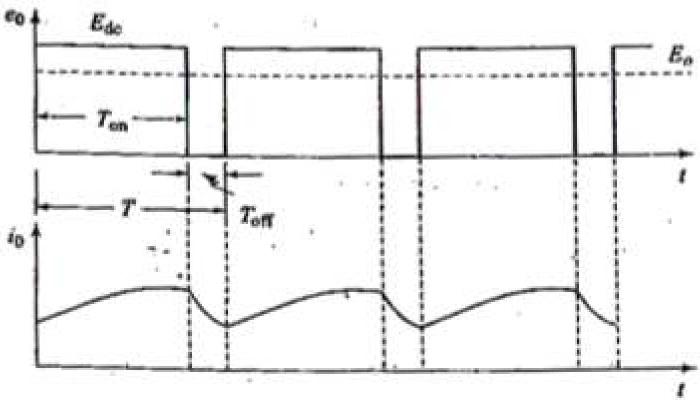


Figure 3-8. DC Chopper output voltage and current waveforms

During the *ON* period of the chopper the input voltage gets applied to the load. During the *OFF* period the load gets short circuited by the freewheeling Diode D_F and the load current flows through D_F. Thus, a chopped voltage is produced across the load. *This is also called Time Ratio control.*

The average output voltage is given by:

$$E_0 = \frac{E_{DC}.T_{ON}}{T_{OFF} + T_{ON}} = E_{DC}.\frac{T_{ON}}{T}$$

Where $\mathrm{T_{ON}} = \mathrm{ON}$ period of the chopper

$T_{OFF} = OFF$ period of the chopper and

$\mathrm{T} = \mathrm{T_{OFF}} + \mathrm{T_{ON}}$ = Chopping period.

$\frac{T_{ON}}{T}$ is called *duty ratio* of the chopper and is represented by the symbol δ.

Then the output voltage E_O is given by**:** $\mathrm{E_O} = \delta.\mathrm{E_{DC}}$

The output voltage E_O is also given by: $\mathrm{E_O} = \mathrm{E_{DC}}.\mathrm{T_{ON}}.\mathrm{f}$

where f is the chopping frequency and is equal to $\frac{1}{T}$

The average value of the load current is given by: $\mathrm{I_O} = \frac{\mathrm{E_O}}{\mathrm{R}} = \delta.\frac{\mathrm{E_{DC}}}{\mathrm{R}}$

3.4.1. Advantages:

- **Voltage Reduction:** Efficiently reduces a higher DC voltage to a lower, regulated DC voltage.
- **High Efficiency:** Compared to linear regulators, choppers are much more efficient as the switch is either fully ON (low voltage drop) or fully OFF (zero current), minimizing power dissipation as heat.
- **Precise Control:** Allows for accurate regulation of the output voltage by adjusting the duty cycle.
- **Compact Size:** Can be designed to be relatively small due to their high efficiency.

3.4.2. Applications:

Step-down choppers are widely used in various applications, including:

- **DC Motor Speed Control:** By varying the voltage supplied to a DC motor, its speed can be precisely controlled.

- **Battery Charging:** Regulating the charging voltage for various battery types.
- **DC-DC Buck Converters:** Used in power supplies for electronic devices (e.g., laptops, smartphones) to step down the input voltage to the required operating voltage.
- **Renewable Energy Systems:** Interfacing solar panels or wind turbines with different voltage requirements.
- **Electric Vehicles and Traction Systems:** For controlling the speed and torque of DC motors in electric cars, trains, and trams.
- **Voltage Regulation in Power Supplies:** Providing stable and regulated DC voltages for various electronic circuits.

3.5. Types of chopper control:

- If the chopper is Transistor based, the base current will switch ON and OFF the transistor.
- If it is GTO thyristor based then a positive gate pulse will switch it ON and a negative gate pulse will switch it OFF
- If it is SCR based a commutation circuit is required to turn it OFF.

3.5.1. Class-A Chopper (First Quadrant operation):

A Class-A chopper, also known as a Type-A chopper or First Quadrant Chopper, is a fundamental type of DC-to-DC converter that operates exclusively in the *first quadrant* of the output voltage (Vo) versus output current (Io) plane. The basic power circuit of a Class-A chopper connected to a separately excited motor operating in the first quadrant is shown in the figure 3-9.

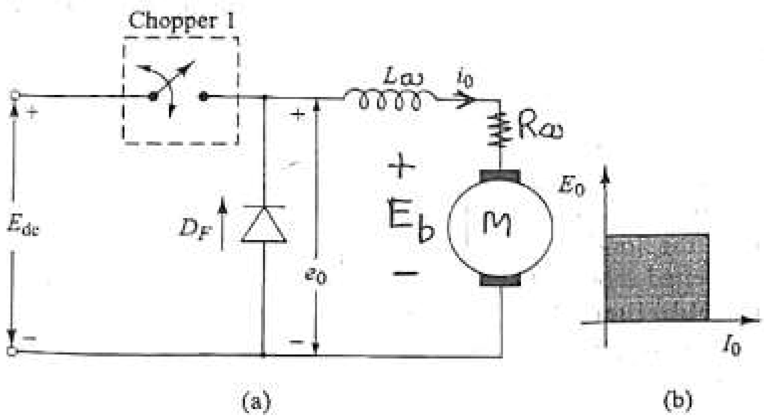


Figure 3-9. First quadrant operation of a Class-A chopper connected to a DC separately Excited motor

The term first quadrant refers to the operation with both voltage E_0 and current I_0 polarities confined to the directions as shown. When the chopper is ON the output voltage $E_O = E_{DC}$ and when the chopper is OFF $E_O = 0$ volts but the current I_O flows in the load in the same direction through the freewheeling diode D_F.

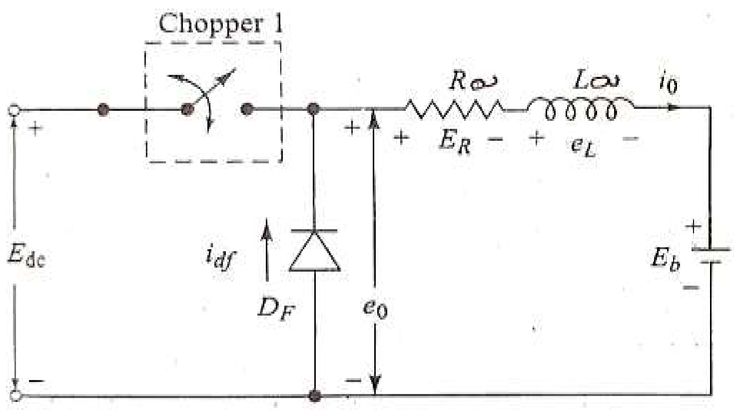


Figure 3-10. Electrical equivalent circuit of Class-A chopper (polarities indicated are when Chopper is ON)

Both average load voltage and load current are positive and hence power flows from source to load. *Hence this is Motoring operation*. The output voltage and current waveforms are shown in the figure 3-11. During the ON period the rate of rise of current is positive and hence the voltage across the Inductance will be positive and the governing relation will be:

$$E_{DC} = R_a . I_0 + L\frac{\mathrm{di_0}}{\mathrm{dt}} + \mathrm{E_b} \quad for\ 0 < t < T_{on}.$$

During the OFF-period rate of rise of current is negative and hence the voltage across the Inductance will be negative and the governing relation will be

$$0 = R_a i_0 + \frac{Ldi_0}{dt} + E_b \ \ for\ T_{on} < t, T$$

The average output voltage E_O is given by $E_O \ = \ E_{DC}.\delta$

where $\delta \ = \ \text{duty ratio} \ = \frac{\mathrm{T_{on}}}{\mathrm{T}}$.

The torque speed relation is identical to those we have seen earlier with single/three phase converters connected to DC SE motors and it is given by:

$$\omega_m = \left(\frac{E_{DC}\delta}{K_a\emptyset}\right) - \left(\frac{R_a T}{(K_a\emptyset)^2}\right)$$

3.5.1.1. Key Characteristics:

- **Step-down operation:** The average output voltage is always less than or equal to the input voltage.
- **Unidirectional power flow:** Power always flows from the source to the load.
- **Unidirectional voltage and current:** Both average output voltage and current are always positive.

3.5.1.2. Applications:

Class-A choppers are commonly used in applications where controlled DC power is needed for a load that only requires power in one direction. Some common applications include:

- **DC Motor Speed Control (Forward Motoring):** They are widely used to control the speed of DC motors in applications like electric vehicles, industrial drives, and traction systems. By varying the duty cycle, the average voltage applied to the motor can be adjusted, thereby controlling its speed.

- **DC Power Supplies and Voltage Regulation:** For providing a variable and regulated DC voltage from a fixed DC source.
- **Battery Chargers:** To control the charging voltage and current for batteries.

3.5.2. Class-B Chopper (Second Quadrant operation):

A Class-B chopper, also known as a **second-quadrant chopper**, is a type of DC-to-DC converter that allows power to flow **from the load back to the source**. This is in contrast to a Class-A chopper (first-quadrant), where power flows from the source to the load.

3.5.2.1. Key Characteristics of Class-B Chopper (Second Quadrant Operation):

- **Output Voltage (Vo) is positive, but Output Current (Io) is negative.** This means the power flow ($P=V_o \times I_o$) is negative, indicating that power is being transferred from the load to the source.
- **Acts as a Step-Up Chopper:** In this mode, the chopper essentially "boosts" the voltage from the load side to a level higher than the source voltage, allowing energy to be fed back into the supply.
- **Requires a DC source in the load:** For a Class-B chopper to operate, the load must contain a DC voltage source (like a battery or the back EMF of a DC motor).
- **Regenerative Braking:** This is the primary application of Class-B choppers, especially in DC motor drives. When a DC motor is in regenerative braking, it acts as a generator, converting kinetic energy into electrical energy. The Class-B chopper then facilitates the return of this electrical energy to the DC supply.

The basic power circuit of a chopper connected to a DC separately excited motor operating in the second quadrant is shown in the figure below. The term second quadrant refers to the operation with both voltage E_0 and current I_0 polarities confined to the directions as shown.

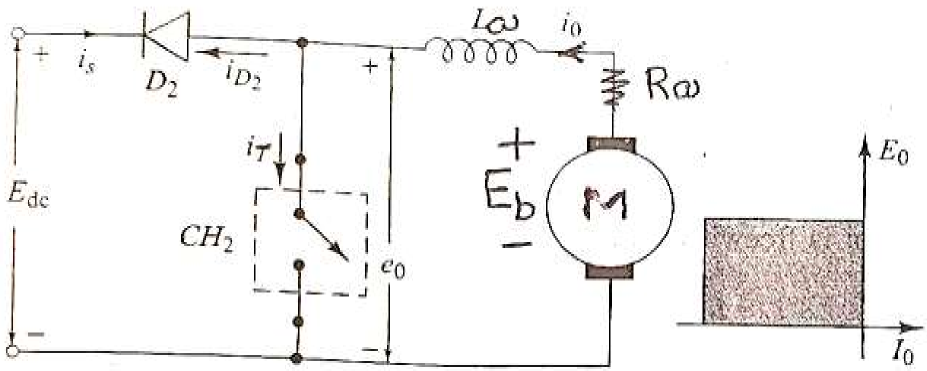


Figure 3-11. Second quadrant operation of a Class-A chopper connected to a DC separately Excited motor

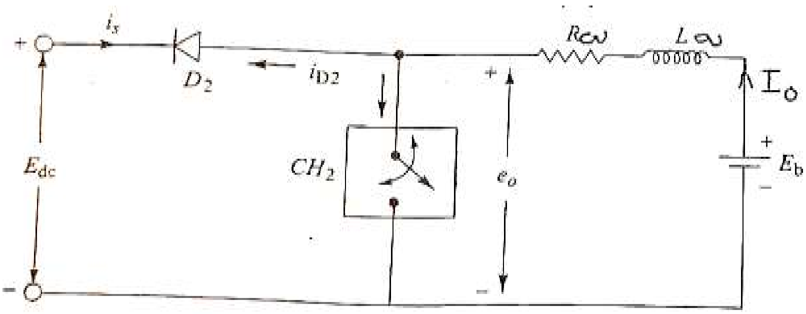


Figure 3-12. Second quadrant operation of a Class-A chopper connected to a DC separately Excited motor along with its equivalent circuit.

Chopper is turned ON and OFF at regular intervals of period T. The back emf E_b stores energy in the inductance L whenever the chopper is ON and this stored energy is delivered to the source E_{DC} by flow of current through the diode D_2 and in the same direction through the motor as it was flowing when the chopper was ON. In this, the average load voltage is positive and load current is negative. Hence power flows from load to source. Hence this is *regenerative braking operation.* The output voltage and current waveforms are shown in the figure 3-13.

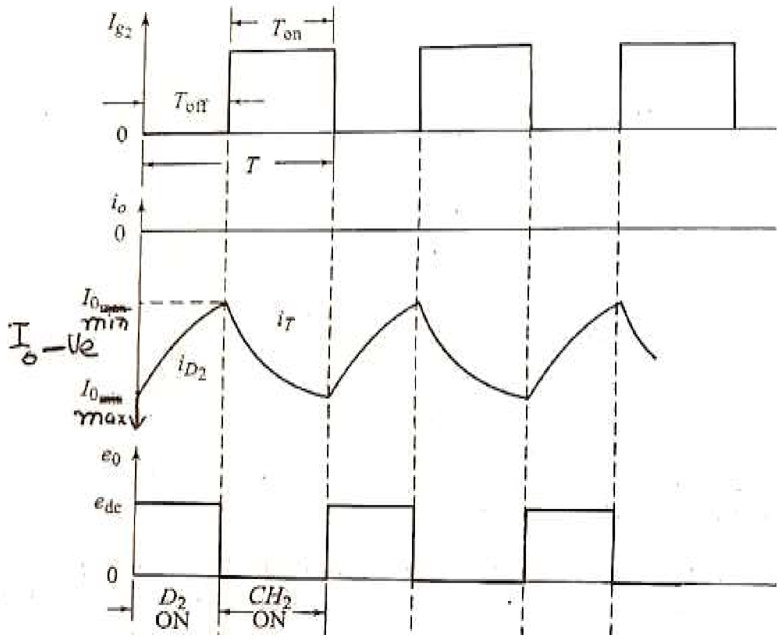


Figure 3-13. Class-B Chopper Voltage and current waveforms with continuous load current

Applications:

The primary application of a Class-B chopper is in:

- **Regenerative Braking of DC Motors:** This allows the kinetic energy of a decelerating motor (e.g., in electric vehicles, trains, elevators) to be converted back into electrical energy and returned to the power supply, improving overall efficiency and reducing heat generation in mechanical braking systems.

3.5.2.2. Chopper control of series motor:

Motoring:

Chopper circuit and the waveforms are same as those of a Class - A chopper connected to a DC separately excited motor. Here also $\mathbf{E_O = E_{DC}.\delta}$ but $\mathbf{E_b}$ will not be constant and varies with i_o. Due to saturation of the field magnetic circuit, relationship between E_b and I_o is nonlinear. However, the basic motor relations we have derived earlier for the series motor are still applicable and are given here again for quick reference.

Since

$$\emptyset = K_f I_a$$

$$E_b = K_a \emptyset \omega = K_a K_f I_a \omega$$

$$T = K_a \emptyset I_a = K_a K I_f^2 a$$

$$E_a = E_b + I_a R_a \ and$$

$$\omega = \frac{E_0}{K_a} K_f I_a - \frac{R_a}{K_a} K_f$$

$$\omega = \frac{E_0}{\sqrt{K_{af} T}} - \frac{R_a}{K_{af}}$$

Where R_a is now the sum of armature and field winding resistances and $K_{af} = K_a . K_f$ is the total motor constant. Using these equations, the torque speed relation for a choppers-controlled DC series motor would become

$$\omega = \frac{E_{Dc}\delta}{\sqrt{K_{af} T}} - \frac{R_a}{K_{af}}$$

Regenerative braking:

For series motor also for regenerative braking the same Class-B chopper that was used for a DC separately excited motor is used. During regenerative braking, series motor works like a self-excited series generator. Bur for self-excitation, the current flowing through the field winding should assist the residual magnetism (as already explained during the braking of series motor). Therefore, when changing from motoring to braking connection, while direction of armature current should reverse, field current should flow in the same direction. This is achieved by reversing the field with respect to armature when changing from motoring to braking operation. Voltage and current waveforms will be same as those shown for regenerative braking of a DC separately excited motor.

The governing equations during braking are:

$E_0 = E_{DC}\ \delta$

$E_a = E_0 + I_a R_a$

$\omega = \frac{E_0}{K_a K_f I_a} + \frac{R_a}{K_a K_f}$

$\omega = \frac{E_{Dc}\delta}{\sqrt{K_{af}T}} + \frac{R_a}{K_{af}}$

For a chosen value of $I_a . K_f$ is obtained from the magnetization characteristic. Then, **ω** and T are obtained from the above equations. The nature of torque speed characteristics is shown in the figure below.

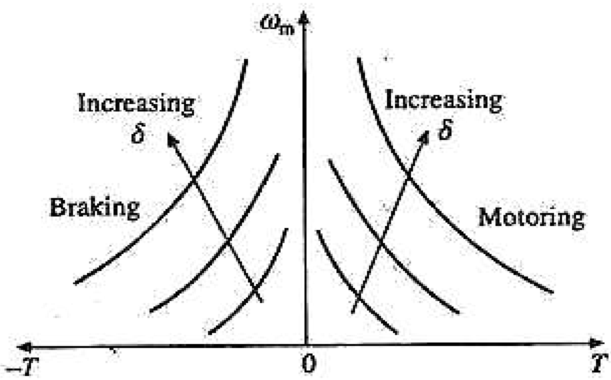


Figure 3-14. Motoring and Regenerative Braking characteristics of a Chopper controlled DC series motor.

3.5.3. Two quadrant (type –A) or class-C chopper:

Class-C chopper can be realized by combining the class-A and class-B choppers together as shown in the figure below. This combined circuit provides both forward motoring and forward regenerative braking. CH1 along with diode D1 performs forward motoring operation while CH2 along with diode D2 performs the function of forward regenerative braking. Thus, for motoring operation CH1 is controlled and for braking operation CH2 is controlled. Shifting of control from CH1 to CH2 shifts operation from motoring to braking and vice versa.

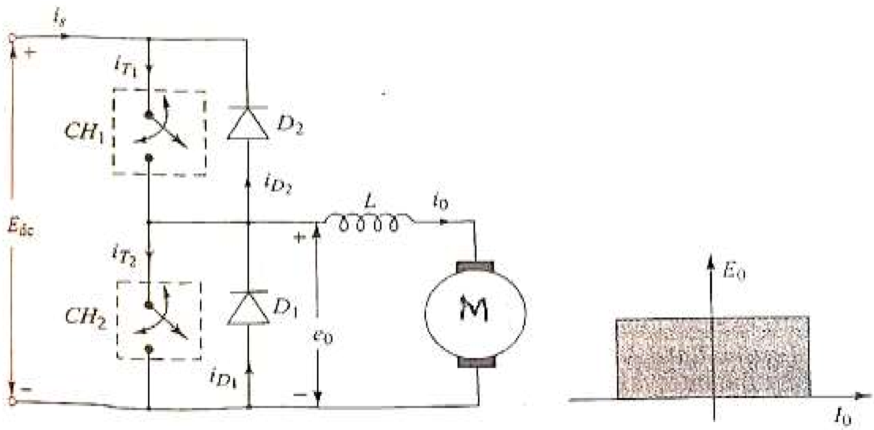


Figure 3-15. Two quadrant Type-A (class- C) Chopper

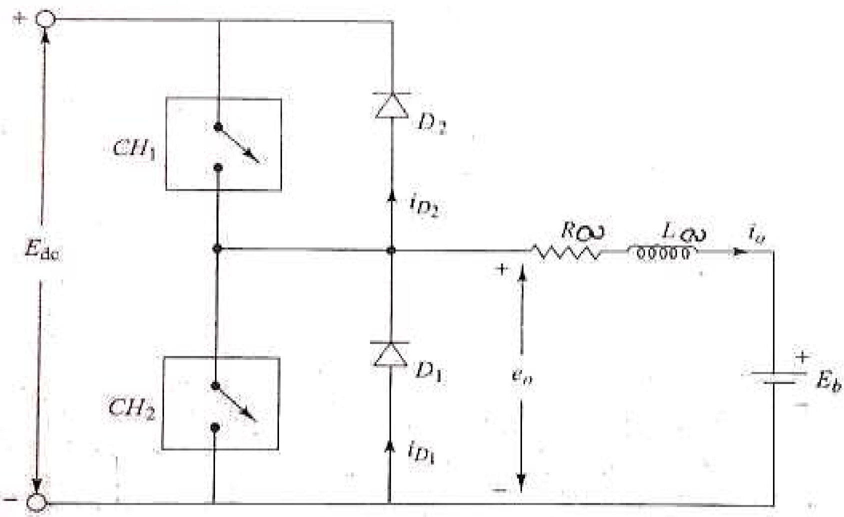


Figure 3-16. Two quadrant Type-A (class- C) Chopper, the permissible E-I coordinates and Electrical equivalent circuit.

But in many applications a smooth and fast changeover from motoring to braking and vice versa is required and in such cases Ch1 and Ch2 are controlled simultaneously as explained below with the help of the Motor terminal voltage and the current waveforms shown in the figure below.

Important points to be noted/conventions followed in this explanation are:

- With the given polarity of E_{DC}, the motor current is positive when flowing down wards (during motoring) and negative when flowing upwards (during braking).
- Since we are considering two quadrant operations with forward motoring & braking, the polarity of E_b is considered positive as shown.
- The choppers conduct in the direction as shown by the arrow in the respective chopper when triggered and only when forward biased.
- The voltage across the inductance is positive (terminal R_a side of L_a is positive as shown in eq. circuit) and adds up to the motor back emf E_b when the rate of rise of current is positive. And this happens when Ch-1 is ON or when diode D2 is conducting.
- The voltage across the inductance is negative (terminal R_a side of L_a is negative as shown in eq. circuit) and opposes the motor back emf E_b when the rate of rise of current is negative. And this happens when Ch- 2 is ON or when diode D1 is conducting.

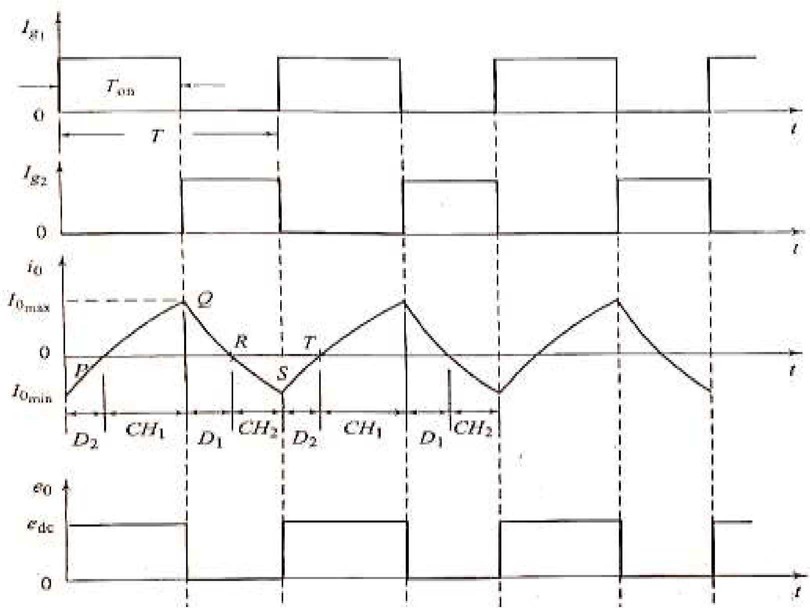


Figure 3-17. Voltage and current waveforms in a Class-C chopper

Operation:

- Initially when both choppers are OFF, both diodes also are not conducting and hence the load is isolated from the source. As shown in the waveforms above, say initially at point P chopperCh1 is triggered and it starts conducting. The load current is positive and the load receives power from the source. So, the output voltage $E_0 = E_{DC}$ whenever chopper Ch1 conducts.
- At point Q chopper Ch1 is turned off, polarity of voltage across inductance L_a changes (becomes negative) and the energy in the inductance forces load current to flow through the diode D1 (in the same direction through the motor i.e., positive) till the voltage across the inductance $L.\frac{di}{dt}$ becomes equal to the back emf E_b and the load current becomes zero i.e., up to point R.
- At this point R, the motor back emf E_b is greater than the voltage across the inductance and since the gate signal for Ch2 is present, now E_b forces a current in the opposite direction (negative current) through La and Ch2.This continues up to point S i.e., until Ch2 is turned off and Ch1 is turned on.
- Now at point S when Ch2 is turned off, polarity of voltage across inductance L_a changes (becomes positive) and the energy in the inductance forces same negative current through the diode D2 into the source until point T when the input current reduces to zero. In this period the current is negative and hence Ch1 cannot conduct though it is triggered.
- At this point T since gate signal is available to Ch1 load current becomes positive, conducts through Ch-1 and the sequence repeats.

Summary observations:

- In a period, T**,** Ch1 is switched on from 0 to δ. T and Ch2 is switched on from $\delta.\mathrm{T}$ to T where **δ** is the duty ratio of Ch1.Therefore during the period 0 to δ.T motor is connected to the source through Ch1 or D2 depending upon whether the motor current is positive (Ch1) or negative (D2).

- Similarly, during the period δ.T to T motor armature is shorted through Ch2 or D1 depending upon whether the motor current is negative (Ch2) or positive (D1). And during this period the rate of change of current is always negative.
- For first quadrant operation i.e., motoring, torque has to be positive, so motor current has to be positive and thus Ch1 and D1 perform the motoring.
- For the second quadrant operation i.e., braking, torque has to be negative, so motor current has to be negative and thus Ch2 and D2 perform the braking.

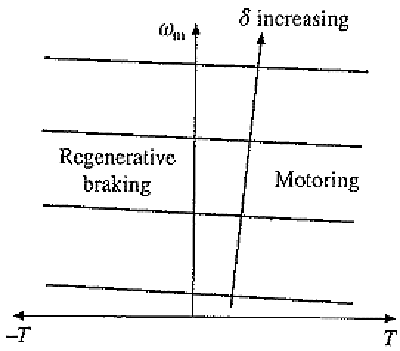


Figure 3-18. Torque speed characteristics of a Class-C chopper-controlled DC separately excited motor.

- Load voltage is zero if either Ch2 or diode D1 conducts and equal to E_{DC} if Ch1 or D2 conducts. So average output voltage is always positive.
- Load current is positive whenever Ch1 or diode D1 conduct and negative when Ch2 or diode D2 conducts.
- Load voltage is positive but current is reversible and hence power flow is also reversible.
- Both Ch1 and Ch2 should not be switched on simultaneously as it would

short circuit the source voltage E_{DC}. They are turned on alternatively as shown by the gate signals I_{g1} and I_{g2}. i.e., I_{g1} and I_{g2} are complementary.

3.5.4. Four Quadrant or Class-E Chopper:

The circuit diagram of a four quadrant or class-E chopper is shown in the figure below. It can be considered to be consisting of either two Class-C or Class-D choppers together as shown. With this type of chopper, motor direction of rotation can be changed without changing the field excitation direction and both motoring and braking operations in both directions can also be obtained by controlling the choppers 1 to 4 as explained below.

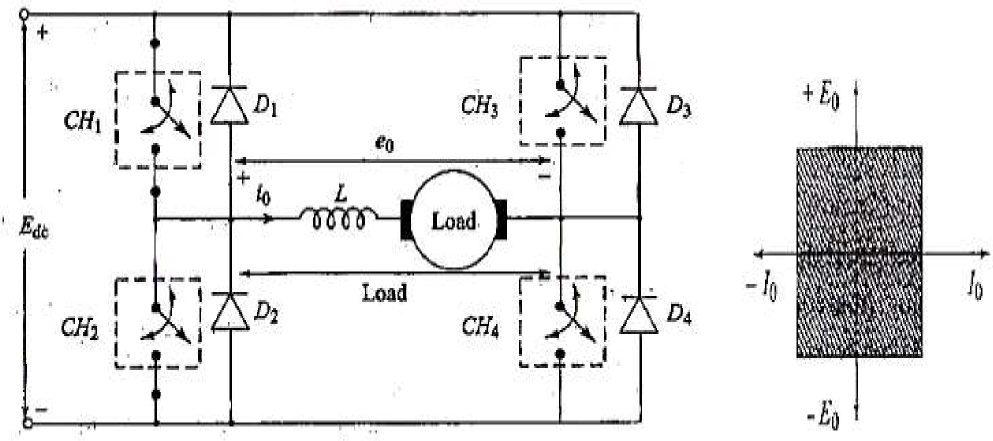


Figure 3-19. Four quadrant or class-E chopper circuit Diagram and characteristic.

With Ch-4 continuously ON and Ch-3 continuously OFF the chopper can be considered to be a Class-C chopper. Controlling choppers 1&2 will make E_o positive and motor current reversible thus operating in first and second quadrants. Similarly with Ch-2 continuously ON and Ch-1 continuously OFF, controlling Ch-3 and Ch-4 will make E_o negative and motor current reversible thus operating in third and fourth quadrants.

3.5.4.1. The operation of a Four Quadrant chopper is explained below

When choppers Ch1 and CH4 are turned ON, current flows through the path:

E_{DC+}, Ch1, load, Ch4, E_{DC--}. Since both E_O and I_O are positive we get First Quadrant operation. When both the choppers Ch1 and Ch4 are turned OFF, load dissipates its' energy through the path: Load, D3, E_{DC+}, E_{DC--}D2, Load. In this case E_O is negative while I_O is positive and we get fourth Quadrant operation. When choppers Ch2 and Ch3 are turned ON current flows through the path: E_{DC+}, Ch3, load, Ch2, E_{DC--}. Since both E_O and I_O are negative we get Third Quadrant operation. When both the choppers Ch2 and Ch3 are turned OFF, load dissipates its' energy through the path: Load, D1, E_{DC+}, E_{DC--}, D4, Load. In this case E_O is positive while I_O is negative and we get Second Quadrant operation.

Four quadrant chopper circuit consists of two bridges, Forward Bridge and Reverse Bridge. Chopper Bridge Ch1 to Ch4 is the forward bridge which permits flow of energy from source to load. Diode Bridge D1 to D4 is the Reverse Bridge which permits flow of energy from load to source. This four- Quadrant Chopper configuration can be used for a reversible regenerative DC drive.

3.5.4.2. Key Features and Advantages:

- **Bidirectional Power Flow:** Can transfer power from source to load and vice-versa.
- **Bidirectional Voltage and Current Control:** Allows for precise control over both the magnitude and polarity of the output voltage and current.
- **Full Motor Control:** Essential for applications like DC motor drives where forward/reverse motoring and regenerative braking are required.
- **High Efficiency:** Compared to some other control methods, choppers offer high efficiency due to the low power loss in switching devices.

3.5.4.3. Applications:

Four-quadrant choppers (Class-E choppers) are widely used in applications that require precise and versatile control of DC power, especially where bidirectional power flow and motor control are essential:

- **DC Motor Drives:** This is one of the most prominent applications, enabling forward/reverse motoring and regenerative braking in electric vehicles, industrial drives, and robotics.

- **Electric Vehicles (EVs):** Used for motor control and regenerative braking to improve energy efficiency.
- **Renewable Energy Systems:** For managing power flow in solar or wind power systems, including battery charging and grid connection.
- **Battery Chargers:** Especially for fast and efficient charging with advanced control capabilities.
- **Railway Systems:** In traction systems for locomotives and trains.
- **Uninterruptible Power Supplies (UPS):** For managing battery charging and discharging.
- **DC Power Supplies and Voltage Regulators:** Where variable and controllable DC output is needed.

Summary:

Important concepts and conclusions:

- Choppers are classified as single quadrant (Class-A&B), two quadrant (Class-C&D) and four quadrants (Class-E) depending on the quadrants of operation.
- They are also classified as step-down and step-up choppers defending on whether the output voltage is lesser than or greater than the input voltage.
- The duty ratio of a chopper is given by $\delta = \text{duty ratio} = \frac{T_{on}}{T}$ where T_{on} is the ON time and T is total time period.
- Choppers conduct in only one direction i.e., when they are forward biased and also when they are triggered to start.
- The voltage across the Armature inductance is positive and adds up to the motor back emf E_b when the rate of rise of current is positive.
  - The voltage across the Armature inductance is negative and opposes the motor back emf E_b when the rate of rise of current is negative

Important formulae and equations:

The output voltage E_O of a chopper is given by: $E_O = \delta . E_{DC}$
The output voltage E_O is also given by: $E_O = E_{DC} . T_{ON} . f$
where f is the chopping frequency and is equal to $1/T$.
The average value of the load current is given by: $I_O = \frac{E_0}{R} = \delta . \frac{E_{DC}}{R}$

Example 3-1.

A 220 V, 24A, 1000 RPM, DC separately excited motor has an armature resistance of 2 Ω. The motor is controlled by a Chopper with a frequency of 500 Hz from a supply of 230 V. Calculate the duty ratio **δ** for 1.2 times the rated Torque and 500 RPM.

Solution:

Given Data:
$E_a = 220\ \text{V}, I_a = 24\ \text{A},\ N = 1000\ \text{RPM}, R_a = 2\ \Omega\ \ E_s = 230\ \text{V}$
(Note: Since the rated voltage of the motor is 220 V which is less than the supply voltage, even for normal operation we have to work with a duty ratio **δ** of 220 / 230 = 0.956 to ensure that never the applied voltage to the motor exceeds 220 V)

First let us find out E_b for 1000 RPM using the relation

$E_a = E_b + I_a R_a$ i.e. $220 = E_b + 24 \times 2$
From which we get $E_b = 220 - 48 = 172\ \text{V}$
for a speed of 1000 RPM
Hence for a speed of 500 RPM $E_b = (\frac{500}{1000}) \times 172 = 86\ \text{V}$

Then the required voltage to be applied to the armature is given by:

$$E_a = (\ E_b\ @\ 500\text{RPM} + I_a\ @\ 1.2 \text{ times rated torque} \times 2)$$
$$= (86 + 24 \times 1.2 \times 2) = 143.6\ \text{V}$$

[Here it is to be noted that the rated current of 24 A is to be multiplied by 1.2 since the motor is now working with a load torque which is 1.2 times the rated torque]

Required E_a for 500 RPM @ 1.2 times rated Torque = 143.6 V
Required duty ratio $\boldsymbol{\delta} = 143.6/230 = 0.624$

Example 3-2.

A DC separately excited motor with an armature resistance of 0.08 Ω is powered by a chopper from a power source of 450V DC. The armature and field currents are 275 A and 3 A respectively. The armature current is continuous and ripple free. Back EMF constant of the motor is K_t = 1.527 V/A. rad/sec. If the duty ratio of the converter is 65% determine:
(i) Input power from the DC source (ii) Speed of the motor and Torque

Solution:

Given Data**:**
$E_s = 450\ \mathrm{V}, I_a = 275\mathrm{A}, If = 3\mathrm{A}, R_a = 0.08\ \Omega,$
$\delta = 0.65, Kt = 1.527\ \mathrm{V/A.rad/sec}$

- Input power is given by the product of the duty ratio, supply voltage armature current.

Thus, IP Power = $\boldsymbol{\delta \times E_s \times I_a = 0.65 \times 450 \times 275 = 80.43\ kW}$

- To find out the speed and the torque we must first be clear of the units of the given motor constant.

We know that motor back EMF and Torque are given by the formulae:
$E_b = K_a \varphi \omega$ and
$T = K_a \varphi I_a$ where the units of K_a are $\mathrm{Vots/Web.Rad/sec}$ or $\mathrm{N-m/Web.Amp}$.

But here the units are given as $\mathrm{V/\mathbf{A}.rad/sec}$. i.e., Assuming the field magnetization to be linear, constant K_f in the relation $\varphi = K_f . I_f$ is combined with K_a in the above relations for Back EMF and Torque thus making them:

$E_b = K_a$

$K_f\, I_f\, \omega$ and $T = K_a\, K_f\, If\, I_a$ or $E_b = K_a f_I\, f_\omega$ and $T = K_{af}\, I_f\, I_a$ where K_{af} is the combined constant of motor including field magnetization and its units are given by:

In case of Back EMF: $V/A.\,rad/sec$ where A (Amperes) refers to the field current and

In case of Torque: $V/A.\,A$ where first 'A' refers to the field current and second 'A' refers to the armature current.

In this problem from the units of the given constant K_t we have to take it as the combined constant K_{af} of the motor including field magnetization.

Now we can directly find out the torque by using the equation:

$T = K_t I_f\, I_a$

Where:

K_t is nothing but K_{af} as explained above and

$T = 1.527 \text{ x } 3 \text{ x } 275 = 1259.7 \text{ N} - \text{m}$

To find out the speed we have to find out the back EMF corresponding to the applied armature voltage with a duty ratio of 0.65 using the standard relation

$E_a = \delta\, E_s = E_b + I_a\, R_a$ from which we get:

$E_b = \delta\, E_s - I_a\, R_a = 0.65 \text{ x } 450 - 275 \text{ x } 0.08 = 292.5 - 22 = 270.5 \text{ V}$
Now from the relation

$E_b = K_{af}\, I_f\, \omega$ we get

$\omega = \frac{E_b}{K_{af}\, I_f} = \frac{270.5}{(1.527 \text{ x } 3)} = 59.04 \text{ Rad/sec}$ and

Speed in RPM $= \left(\frac{59.04}{2\pi}\right) 60 = 564 \text{ RPM}$

Example 3-3:

A DC separately excited motor with an armature resistance of 2 Ω is powered by a chopper from a power source of 220V DC. The chopper is working with an ON time of 15 msec and OFF time of 10 msec. The motor constant K_m = 0.4 V/Rad/sec. Assuming continuous current conduction calculate the average motor current for a speed of 1400 RPM.

Solution:

Given Data**:**

$Es = 220\ V, R_a = 2\ \Omega, K_m = 0.4\ V/Rad/sec,$
$t_{ON} = 15\ mses, t_{OFF} = 10\ mses$

From the given units of the motor constant and the standard back EMF relation $E_b = K_a.\Phi.\omega$ we can easily see that it is normal motor constant K_a combined with a constant flux φ resulting in a simpler relation

$E_b = K_m\,\omega$ where $K_m = K_a.\Phi = 0.4\ V/Rad/sec$

To calculate I_a we have to use the standard DC motor relation:

$E_a = E_b + I_a R_a$

We know R_a. We have to find out E_a & E_b then we can find out I_a

$E_a = \delta.E_s$ where $E_s = 220\ V$ and $\delta = \frac{t_{ON}}{\text{Total period}}$

$T = \frac{t_{ON}}{t_{ON}+t_{OFF}} = \frac{15}{15+10} = \frac{15}{25} = 0.6$

Thus $E_a = 0.6 \times 220 = 132\ V$

E_b = Speed in Rad/sec (Speed in RPM x $2\pi/60$) x Km = 146.5 x 0.4 = 58.6 V

From the basic DC motor relation we get

$$\mathbf{I_a} = \frac{(E_a - E_b)}{R_a} = \frac{132 - 58.6}{2} = \frac{73.4}{2} = 36.7A$$

Example 3-4

A separately excited DC motor with an armature resistance of 0.01 Ω works on a DC supply of 220 V. It draws an armature current of 100A and its rated speed is 1000 RPM. It is fed from a chopper controller for its motoring and braking operations. Assuming continuous conduction

- Calculate the duty ratio of chopper at rated torque with a speed of 500RPM during motoring
- Calculate the duty ratio of chopper at rated torque with a speed of 500RPM during braking

Solution:

Given Data: $E_a = 220\ V, I_a = 100A, N = 1000\ RPM, R_a = 0.01\ \Omega$
Motoring operation Governing equation is:

$$E_a = E_b + I_a\, x\, R_a \quad \text{i.e.} \quad 220 = E_b + 100\, x\, 0.01$$

From which we get E_b at rated

$$1000\ RPM = 220 - 100\, x\, 0.01 = 220 - 1 = 219\ V$$

$$Eb\ at\ 500\ RPM = \left(\frac{500}{1000}\right) x\, 219 = 109.5\ V$$

Required terminal voltage during braking is given by

$$E_a = E_{b@500RPM} + I_a\, x\, R_a = 109.5 + 100\, x0.01 = 110.5\ V$$

From which we get; Required duty ratio $\delta = \frac{110.5}{220} = 0.5$

Required terminal voltage E_a during braking is given by

$$E_a = E_{b@500RPM} - I_a\, x\, R_a = 109.5 - 100\, x0.01 = 108.5\ V$$

From which we get: Required duty ratio $\boldsymbol{\delta} = 108.5/220 = \mathbf{0.493}$

Example 3-5:

A separately excited DC motor is controlled by an ideal step-down chopper with an ideal voltage source of 230 V. Motor armature resistance R_a = 1.5 Ω, L_a = 1mH, motor back emf constant = 0.05 volts/rpm. The motor drives a load with constant Torque drawing an average current of I_a = 15 A. Obtain

- The range of speed control
- Corresponding range of duty ratio.

Solution:

Minimum speed /corresponding duty ratio of motor: Here we have to start with *minimum speed as zero* and find out the corresponding δ. To find out the required δ we have to find out the required E_a taking E_b as zero corresponding to zero speed.

i.e., $E_a = E_b + I_a R_a = 0 + 15 \text{x} 1.5$ (Since Torque is constant and corresponding $I_a = 15) = 22.5\,\text{V} = \delta \,\text{x}\, 230$ from which we have $\delta = 22.5 / 230 = 0.097$

For finding out maximum speed and the corresponding maximum duty ratio δ: the procedure is different. Here we have to start with *maximum δ as 1* and then find out the maximum speed.

With δ as 1 we have

$$E_s = 1 \,\text{x}\, 230 = 230 \text{ V} = E_b + I_a R_a = E_b + 15 \,\text{x}\, 1.5$$

from which we get: $E_b = 230 - 22.5 = 207.5\,\text{V}$

Now maximum speed can be obtained using the relation E_b = N x K (where N is in RPM and motor back emf constant K is = 0.05 Volts /RPM and E_b = 207.5 Volts) from which we get

$207.5 = N_{max} \times 0.05$ and thus $N_{\text{max}} = \frac{207.5}{0.05} = 4150$ RPM.

Thus, to get a Speed range of 0 to a maximum of 4150 RPM the required δ range is: 0.097 to 1.0

Example 3-6:

A DC shunt motor draws a current of 50 A on a DC supply of 440 V and runs at 1000 RPM. It has an armature resistance of 0.5 Ω & field resistance of 100 Ω and is connected to a load having a constant torque. Its armature is controlled by a Chopper with an ON period of 2ms in the speed range of 400- 800 RPM. The field current is held constant from a separate DC supply of 440V. Determine the range of frequencies of the chopper to get the required speed range.

Solution:

Given Data:

$E_S = 440\, V, I_A = 50\, A,$

$Speed\ N = 1000\, RPM, R_A = 0.5\, \Omega\ RF = 100\, \Omega$

Range of speed required $= 400\ to\ 800\ RPM\ t_{ON} = 2\, ms$

It is to be noted here that since the chopper is operated at a constant ON period of 2 ms, to get a variable duty ratio δ, we have to vary the chopper frequency f. The first step is to find out the back emf E_b of the motor at the rated speed of 1000 RPM when it is running with full supply voltage of 440 V

Back EMF E_b at rated speed of 1000 RPM $= E_S - I_A R_A$

$= 440 - 50\, x\, 0.5 = 415\, V$

The next step is from this value of E_b we can find out the back emfs corresponding to the two speeds and from them, the required armature voltages, then the required duty ratios and then finally the required chopper frequencies.

To find out chopping frequency for lower end of speed i.e., 400 RPM:
Back EMF E_b at lower end speed of

400 RPM $= 415 \text{ x } 400 / 1000 = 166$ V

The required armature supply voltage for this speed

$E_S = E_b + I_A R_A = 166 + 50\,x$
$0.5 = 191\,V$

(Current is taken here as the rated current of 50 A since the load torque is given to be constant)

Hence δ x 440 = 191 V

from which we get $\delta = \frac{191}{440} = 0.434$ But

$\delta = \frac{t_{on}}{\text{Chopping period}} = 2 \text{ x } 10^{-3} \times$ Chopping frequency 'f'

(Since Chopping frequency $= \frac{1}{\text{Chopping period T}}$)

Hence chopping frequency 'f' required to get 400 RPM

$= \frac{\delta}{(2 \text{ x } 10^3)} = \frac{0.434}{(2 \text{ x } 10^3)} = 0.117 \text{ x } 10\ 3 = 117$ Hz

To find out chopping frequency for upper end of speed i.e., 800 RPM:

Back EMF E_b at upper end speed of 800 RPM = 415 x 800 /1000 = 332 V

The required armature supply voltage for this speed

$E_S = E_b + I_A R_A = 332 + 50 \times 0.5 = 357\,V$

Hence δ x 440 = 357V from which we get δ = 357 /440 = 0.811

But $\delta = \frac{t_{ON}}{\text{Chopping period}} = 2 \text{ x } 10^{-3} \times$ Chopping frequency 'f'

Hence, we get choping frequency 'f' required to get 800 RPM

$= \frac{\delta}{2} \times 10^{-3} = \frac{0.811}{(2 \times 10^{-3})} = 0.4055\,x\,10\ 3 = 405.5\,Hz$

Hence the Range of chopping frequencies is 117 Hz to 405.5 Hz to get a range of speeds from 400 to 800 RPM. (It is to be noted that sometimes all the given data in the problem may not be required to get the required solution. For e.g.in this problem field voltage and field resistance are not required to get the required solution.)

Example 3-7:

A 230 V, 500 RPM, 4.1A, DC 1 HP motor has an armature resistance of 7.56 Ω and inductance of 55.0 mH. Its armature is controlled by a class A Chopper with a 240 V DC source. The field current is held constant at a value that gives rated operation on 230V DC at a chopping frequency of 50 Hz. The minimum load torque is 5 $N-m$. Determine the value of t_{ON} for the minimum load Torque of 5 $\mathrm{N-m}$ at rated speed of 500 RPM

Solution:

Given Data:

$E_s = 240\ \mathrm{V}, E_a = 230, I_a = 4.1\mathrm{A}, R_a = 7.56\ \Omega$

Output Power = 1 HP = 746 watts, Rated speed = 500 RPM
From Rated speed in RPM we get rated speed in Rad/sec as:

$$\omega = \frac{2\pi N}{60} = 2\pi.\frac{500}{60} = 52.36\ \mathrm{Rad/sec}$$

Then let us get the back e.m.f at the rated speed as:

$$E_b = E_a - I_a R_a = 230 - 4.1 \times 7.56 = 199\ \mathrm{Volts}$$

We know that $E_b = K_a \varphi \omega$ from which we get the motor constant $K_a \varphi$ as:

$$K_a \varphi = \frac{E_b}{\omega} = \frac{199}{52.36} = 3.801\ \mathrm{Volts/Rad/sec\ or\ N-m/Amp}$$

(Here we have considered the motor constant as $K_a\varphi$ instead of just K_a i.e. including φ since we are have data as constant field current and constant flux φ)

To find out t_{ON} we have to follow the following sequence:

From the given data first find out the mechanical torque losses as below:

Armature Input Power = $E_a I_a = 230\ x\ 4.1 = 943\ watts$
Actual output power is given as (or shaft power) = 1 HP = 746 watts

Armature Copper losses = $I_a^2 R_a = (4.1)^2 \times 7.56 = 127$ watts

Mechanical rotational power losses = Armature Input Power – (Actual Motor output power + Armature Copper losses)

$= 943 - (746 + 127) = 70\ Watts$

Hence, we have @500 RPM rotational torque loss

$$\tau_{loss} = \left(\frac{Rotational\ power\ loss\ @500RPM}{\omega}\right) = \frac{70}{52.36} = 1.337N - m$$

Now we can find out t_{ON} as below:

For minimum load torque @500 RPM the average internal torque developed by the motor:

$\tau_d = \tau_{min} +$ rotational torque loss $= 5 + 1.337 = 6.337$ N − m

We know that the torque developed by the motor is given by $\tau_d = K_a\varphi . I_a$ from which we have: $I_a = \frac{\tau_d}{K_{a\varphi}} = \frac{6.337}{3.801} = 1.667$ Amp (corresponding to the minimum torque)

Hence the required armature voltage

$$E_a = E_{b@500rpm} + I_a R_a = 199 + 1.667 \times 7.56 = 211.6\ V$$

We know that on time t_{ON} is given by $t_{ON} = \left(\frac{E_a}{E_s}\right) \times T$

Where:

E_a = Required armature voltage = 211.6 V

E_s = Supply DC voltage = 240 V

T = Time period (corresponding to a chopping frequency of 50 Hz) $= \frac{1}{50}$ sec

From which we have

$$t_{ON} = \left(\frac{211.6}{240}\right) \times \left(\frac{1}{50}\right) = 1.763 \times 10^{-3}\ Sec = 1.763\ m\ Sec$$

(It is to be noted that sometimes all the given data in the problem may not be required to get the required solution. For e.g. in this problem armature inductance is not required to get the required solution.)

Chapter-4. Control of Induction Motor through Storage Voltage and Frequency

4.1. Review of Basic Induction Motor Concepts:

Induction motors are workhorses in electrical drive systems due to their robustness, simplicity, and relatively low cost. Understanding their fundamental concepts is crucial for anyone working with electrical drives. Here's a breakdown:

An induction motor (also known as an asynchronous motor) is an AC electric motor that converts electrical energy into mechanical energy through electromagnetic induction. Unlike DC motors or synchronous motors, it doesn't require a direct electrical connection to its rotor.

Induction motors are workhorses in electrical drive systems due to their robustness, simplicity, and relatively low cost. Understanding their fundamental concepts is crucial for anyone working with electrical drives. Here's a breakdown:

4.1.1. What is an Induction Motor?

An induction motor (also known as an asynchronous motor) is an AC electric motor that converts electrical energy into mechanical energy through electromagnetic induction. Unlike DC motors or synchronous motors, it doesn't require a direct electrical connection to its rotor.

4.1.2. Key Components:

- **Stator:** This is the stationary part of the motor. It consists of a laminated steel core with windings (coils) embedded in slots. When an AC voltage is applied to these windings, it creates a rotating magnetic field (RMF).
- **Rotor:** This is the rotating part, housed inside the stator. There are two main types:
    - **Squirrel Cage Rotor:** The most common type. It has conductive bars (typically aluminum or copper) embedded in a laminated steel core, short-circuited at both ends by end rings, resembling a squirrel cage.
    - **Wound Rotor:** This type has a three-phase winding similar to the stator, connected to external resistors or controllers via slip rings. This allows for better control over starting torque and speed.
- **Air Gap:** The small space between the stator and the rotor.

4.1.3. Working Principle (Electromagnetic Induction):

The operation of an induction motor relies on Faraday's Law of Electromagnetic Induction and Lenz's Law:

- **Rotating Magnetic Field (RMF) in the Stator:** When a three-phase AC supply is applied to the stator windings, it creates a magnetic field that rotates at a constant speed called the **synchronous speed (Ns)**. This speed is determined by the frequency of the AC supply (f) and the number of poles (P) in the motor's stator windings:

  $N_s = \frac{120 \times f}{P}$ $(in\ RPM)$

- **Induction in the Rotor:** As the stator's RMF sweeps across the rotor conductors, it cuts through them. According to Faraday's Law, this induces an electromotive force (EMF) and, consequently, currents in the short-circuited rotor conductors.

- **Production of Torque:** These induced currents in the rotor create their own magnetic field. According to Lenz's Law, the rotor's magnetic field will interact with the stator's rotating magnetic field to oppose the change that caused it (the relative motion). This interaction generates a torque that causes the rotor to rotate in the same direction as the RMF.
- **Asynchronous Operation (Slip):** The rotor can never reach the synchronous speed of the stator's magnetic field. If it did, there would be no relative motion between the rotor conductors and the RMF, no induced EMF, and thus no current or torque. Therefore, the rotor always lags behind the synchronous speed. This difference in speed is called **slip (s)**.

$$s = \frac{N_s - N_r}{N_s}$$

where Nr is the rotor's actual mechanical speed. Slip is usually expressed as a percentage or a per-unit value and is crucial for generating torque. A small slip indicates high efficiency, while higher slip leads to greater torque but lower efficiency.

4.1.4. Key Concepts in Electrical Drives:

- **Torque-Speed Characteristic:** Understanding how torque varies with speed is fundamental. Induction motors typically have a relatively linear torque-slip characteristic in their normal operating range. There's a starting torque, a maximum or "breakdown" torque, and a full-load torque.
- **Starting Current:** Induction motors draw a very high current at startup (often 5-7 times the rated current) because the slip is maximum (rotor is stationary). This can cause voltage dips and stress on the power system and motor windings.
- **Starting Methods:** Various methods are employed to reduce the high

starting current, such as:

  - Direct-On-Line (DOL) starting (for smaller motors)
  - Star-Delta starting
  - Auto-transformer starting
  - Rotor resistance starting (for wound rotor motors)
  - Soft starters (using power electronics)

- **Speed Control:** Traditionally, induction motors were considered constant-speed machines. However, with the advent of power electronics, particularly **Variable Frequency Drives (VFDs)** or Adjustable Speed Drives (ASDs), precise and efficient speed control is now possible. VFDs change the frequency and voltage supplied to the motor, thereby controlling the synchronous speed and allowing the motor to operate at various speeds while maintaining good efficiency.
- **Efficiency:** Induction motors are generally highly efficient, especially at full load. Drive systems aim to maximize overall efficiency, considering both motor and drive losses.
- **Power Factor:** Induction motors operate with a lagging power factor, especially at light loads. This is due to the magnetizing current required to establish the magnetic field. Power factor correction techniques might be employed in drive systems.
- **Applications in Electrical Drives:** Induction motors, especially with VFDs, are widely used in a vast array of electrical drive applications, including:
  - Pumps and fans (where variable speed saves significant energy)
  - Conveyor belts
  - Machine tools
  - HVAC systems
  - Cranes and hoists (especially with wound rotor motors for high starting torque)
  - Electric vehicles (EVs)

4.1.5. Principle of operation:

The Development of Induced Torque in an Induction Motor:

- When current flows in the stator, it will produce a magnetic field in stator such that B_s (stator magnetic field) will rotate at a speed: $\mathrm{n_S} = 120.\frac{\mathrm{f_S}}{\mathrm{P}}$
- Where f_s is the system frequency in hertz and P is the number of poles in the machine. This rotating magnetic field B_s passes over the rotor bars and induces a voltage in them. The voltage induced in the rotor is given by:

$e_{ind} = (V \times B)l$

Where:

v = velocity of the Rotor bars relative to the Stator magnetic field,
B = magnetic flux density vector and
l = length of the rotor bar in the magnetic field.

- Hence there will be a rotor current flow which would be lagging due to the fact that the rotor is Inductive. And this rotor current will produce a magnetic field at the rotor, B_r. The Interaction between these two magnetic fields would give rise to an induced torque:

$$T_{ind} = K.B_R \times B_s$$

- The torque induced would accelerate the rotor and hence the rotor will rotate.
- However, there is a finite upper limit to the motor's speed due to the following interactive phenomenon:

If the induction motor's speed increases and reaches synchronous speed then the rotor bars would be stationary relative to the magnetic field

↓

No induced voltage

↓

No rotor current

↓

No rotor magnetic field

↓

Induced torque = 0

↓

Rotor will slow down due to friction

An induction motor can thus speed up to such a near synchronous speed where the induced torque is just able to overcome the load torque but it can never reach synchronous speed.

4.2. Rotor Slip

Rotor slip is a fundamental concept in AC induction motors, which are widely used in electric drives. It's the key phenomenon that enables the motor to produce torque.

In an AC induction motor, the stator (stationary part) winding, when supplied with AC power, creates a rotating magnetic field. This field rotates at a constant speed called the *synchronous speed (Ns)*.

The rotor (rotating part) of an induction motor is not directly connected to the power supply. Instead, current is induced in the rotor conductors due to the relative motion between the rotating magnetic field and the rotor conductors. For this induction to occur, the rotor must always lag behind the rotating magnetic field. This difference in speed is called *slip*.

Essentially, slip is the difference between the synchronous speed of the stator's magnetic field and the actual mechanical speed of the rotor.

4.2.1. Why is Slip Necessary?

- **Torque Production:** If the rotor were to rotate at the same speed as the synchronous magnetic field (i.e., zero slip), there would be no relative motion between the rotor conductors and the magnetic field. Consequently, no electromotive force (EMF) would be induced in the rotor, no current would flow, and no electromagnetic torque would be produced. Therefore, a certain amount of slip is essential for the motor to operate and generate torque.
- **Induction Principle:** The operation of an induction motor relies on Faraday's law of electromagnetic induction. For induction to occur, the magnetic field must "cut" across the rotor conductors, which requires a difference in speed.

The induced voltage in the rotor bar is dependent upon the *relative speed between the stator Magnetic field and the rotor*. This is termed as slip speed and is given by:

$$n\ slip = n_{sync} - n_m$$

Where:

n_{slip} = slip speed of the machine
n_{sync} = speed of the magnetic field (also motor's synchronous speed) and
n_m = mechanical shaft speed of the motor.

Apart from this we can describe this relative motion by using the concept of *slip* which is the relative speed expressed on a per-unit or percentage basis. *Slip* ***s*** is defined as

$$S = \frac{n_{slip}}{n_{sync}} \times 100\%$$

$$S = \frac{n_{sync} - n_m}{n_{sync}} \times 100\%$$

On percentage basis and is defined as

$S = \frac{N_{sync} - N_m}{N_{sync}}$ on per unit basis.

Slip S is also expressed in terms of angular velocity $\boldsymbol{\omega}$ (Rad/Sec) as given below:

$S = \frac{\omega_{sync} - w_m}{\omega_{sync}} \times 100\%$

It can be noted that if the motor runs at synchronous speed the slip $S = 0$ and if the rotor is standstill, then the slip $S = 1$. It is possible to express the mechanical speed of the Rotor in terms of Slip $\boldsymbol{S}$ and synchronous speed $n_{sync.}$

In case of a transformer, the frequency *'f'* of the induced $e.m.f$. in the secondary is same as that of the voltage applied to the primary. But in the case of an Induction motor, it is not same as that of the applied voltage to the stator and depends on the slip. At start, the speed N = 0, the slip 's'= 1 and the frequency of the induced voltage in the rotor is same as that of the voltage applied to the stator. As the motor picks up speed, the slip becomes smaller and hence the frequency of the induced $e.m.f.$ in the rotor also becomes lesser. Due to this, some of the Rotor parameters also get affected. Let us study the effect of slip on the following parameters. 1. Rotor frequency 2. Magnitude of induced $e.m.f.$ 3. Rotor reactance 4. Rotor power factor and 5. Rotor current.

4.2.2. Rotor frequency:

speed of the Stator rotating magnetic field is given by

$$N_S = 120.\frac{f_S}{P} \qquad (4.a)$$

where:

f_s is the system frequency in hertz and,

P is the number of poles in the machine.

At start, the speed N = 0, the slip 's'= **1** and the rotor which is stationary has maximum relative motion i.e., same as that of the $R.M.F$. Hence the frequency of the induced voltage in the rotor is same as that of the voltage applied to the stator. As the motor picks up speed the relative speed of the Rotor with respect to the Stator RMF decreases and becomes equal to slip speed $(N_S - N)$. As we know, the frequency and Magnitude of induced $e.m.f$ in the rotor depends on the rate of change of cutting flux i.e., relative speed (N_S- N). Hence in running condition the magnitude and frequency of induced voltage decreases. The rotor is wound for the same number of poles as that of the Stator i.e., P. If f_r is frequency of the Rotor induced e.m.f. in running condition at slip speed of $(N_S - N)$ (when the motor is running at a speed of N) then there exists a fixed relation between slip speed $(N_S - N)$, f_r and P just as in the case of stator. So, for Rotor we can write:

$$N_s - N = \frac{120 f_r}{P} \qquad (4.b)$$

Dividing equation (2) by (1) we get:

$$(N_s - N)/N_s = (\frac{120 f_r}{P}) / (120.\frac{f_S}{P})$$

But $\frac{N_S - N}{N_s} =$ Slip's'

Hence $S = \frac{F_r}{F_s}$ $or\ f_r = Sf_s$

Thus, we can say that the frequency of the Rotor induced $\boldsymbol{e.m.f}$ $\boldsymbol{f_r}$ is slip 's 'times the supply frequency $\boldsymbol{f_s}$.

As slip of an induction motor is normally in the range of 0.01 to 0.05 the Rotor frequency is very small in the running condition.

4.2.3. Rotor Induced *e.m.f*:

We know that just like the induced frequency, the induced $e.m.f$ is also is proportional to the relative speed between the Rotor and the stator.

Let

E_2 = Rotor induced e.m.f when it is standstill i.e., relative speed is N_s

And

E_{2r} = Rotor induced $e.m.f$ when it is running i.e., relative speed is $N_s - N$

So, we have $E_2 \propto N_s$ i. e $E_2 = k\,N_s$ **----- (1)**

And $E_{2r} \propto N_s - N$ i. e $E_{2r} = k\,(N_s - N)$ ----- (2)

Dividing the second equation by first equation we get:

$$\frac{E_{2r}}{E_2} = \frac{(N_s - N)}{N_s}$$

$$But\ \frac{N_s - N}{N_s} = slip's.$$

Hence, we get finally:

$$E_{2r} = s\,E_2$$

i.e., The magnitude of the *Rotor* $e.m.f.$ *in running condition* also gets reduced to slip times the magnitude of the $e.m.f.$ *in standstill condition*.

4.2.4. Rotor Resistance and Reactance:

Just like the stator, Rotor winding also has its own Resistance and Reactance and let them be $R_2\ \Omega\ /Ph$ and $X_2\ \Omega\ /Ph$ respectively. We know that Resistance of a coil is independent of frequency while its Reactance is given by $X = 2\pi fL$ where L is the Inductance of the coil. Thus $X_2\ (@\ standstill\ ) = 2\pi f_s L$
and since $f_r = s f_s$

$$X_{2r}\ (\ @\ \text{running condition}\ ) = 2\pi f_r L = 2\pi s f_s L = sX_2$$

$\boldsymbol{i.e. X_{2r} = s X_2}$

Thus, we can conclude that the Resistance of the Rotor which is independent of frequency remains the same at both standstill and in running condition while the reactance which is dependent on the frequency gets reduced to slip times the Reactance in standstill condition.

Then we have Rotor impedance Z_2 per phase as:

$Z_2 = R_2 + j X_2 = \sqrt{R_{22} + X_{22}}\ \Omega /Ph$ (At standstill)

And $Z_{2r} = R_2 + jX_{2r} = \sqrt{R_{22} + (sX_2)^2}\ \Omega /Ph$ (at Running condition)

4.2.5. Rotor power factor:

We know that the power factor of any inductive circuit is given by:

$$\boldsymbol{Cos\ \theta = \frac{R}{Z}}$$

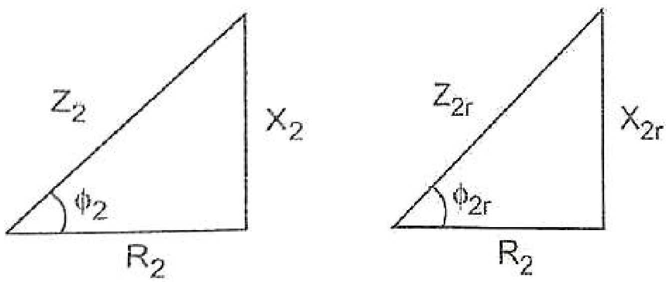


Figure 4-2. Impedance triangles (a) at standstill and (b) while running

Using the above values of Resistance and impedance of the Rotor in both standstill and running conditions in this relation for power factor we get:

$cos\theta = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2+(sX_2)^2}}$ (At standstill) and

$$cos\theta_r = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2+(sX_2)^2}} \text{(At Running condition)}$$

The corresponding impedance triangles for both standstill and running conditions are shown in the figure 4.1(a) and (b).

Note: As Rotor circuit is inductive the p.f is always lagging.

4.2.6. Rotor current:

The rotor currents (per phase) in both cases are given by (using the basic relation $I = \frac{E}{Z}$)

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R\ 22\ + j\ X\ 22}} \text{(At standstill) and}$$

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{E_{2r}}{\sqrt{R_2^2}} + j\,X_2 r_2 = sE_2/R_2^2 + (sX_2)^2 \qquad \text{(At Running condition)}$$

Note: (θ_{2r} is the phase angle between the Rotor voltage E_{2r} and Rotor current I_{2r} which decides the power factor while the motor is running). The corresponding Rotor equivalent circuits for both standstill and running conditions are shown in the figures (a) and (b) below.

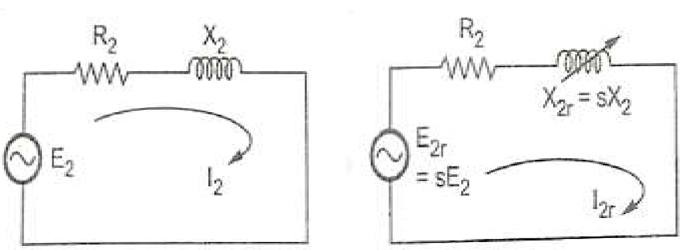


Figure 4-3. Rotor equivalent circuit (a) At standstill (b) while running

Rotor power input, Rotor copper loss and mechanical power developed and their interrelation:

An induction motor can be basically described as a rotating transformer. Its input is a 3-phase system of voltages and currents. For an ordinary transformer, the output is electric power from the secondary windings. The secondary windings in an induction motor (the rotor) are shorted and so no electrical output exists from normal induction motors. Instead, the output power is mechanical. The power flow diagram given below shows how the Input Electrical power given to the Induction Motor stator gets converted into Mechanical power at the Rotor end and what are the losses taking place in between.

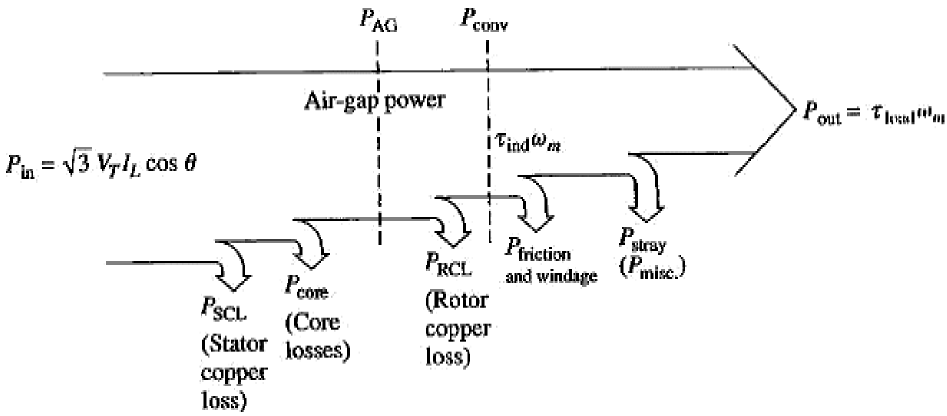


Figure 4-4. Power flow diagram of an Induction motor.

The input power to an induction motor P_{in} is in the form of 3-phase electric voltages and currents and is given by:

$$P_{IN} = \sqrt{3\, V_L I_L \cos\theta}$$

where V_L , I_L are line values of voltage & current and $cos\ \theta$ is motor power factor.

The first losses encountered in the machine are I^2R losses in the stator windings (the stator copper loss P_{SCL}). Then, some amount of power is lost as hysteresis and eddy currents in the stator (P_{core}). The power remaining at this point is transferred to the rotor of the machine across the air gap between the stator and rotor. This power is called the air gap power P_{AG} of the machine.i.e.

$$P_{AG} = P_{IN} - (P_{SCL} + P_{core}) = T_{ind}.\omega s$$

After the power is transferred to the rotor, some of it is lost as I^2R losses (the rotor copper loss P_{RCL}), and the rest is converted from electrical to mechanical form (P_{CONV}).i.e.

$$P_{CONV} = P_{AG} - P_{RCL} = T_{ind}.\omega m$$

When this mechanical power is delivered to the load through the rotor shaft again some more power is lost as mechanical losses known as friction and windage losses P_{FW} and then again, some unaccounted losses known as stray losses P_{MISC}. Finally, the remaining power is the net output power delivered by the Motor to the load as P_{OUT} i.e.

$$P_{OUT} = P_{M} - (P_{FW} + P_{MISC}) = T_{load}.\omega m$$

This total power flow along with the losses in between is shown the diagram above.

The core losses do not occur in the stator side alone as shown in the figure above. The core losses of an induction motor come partially from the stator circuit and partially from the rotor circuit. Since an induction motor normally operates at a speed near synchronous speed, the relative motion of the magnetic fields over the rotor surface is quite slow, and the rotor core losses are very tiny compared to the stator core losses. Since the largest fraction of the core losses come from the stator circuit, all the core losses are lumped together and shown as if they are occurring at the stator end. The *higher* the speed of an induction motor, the *higher* the friction, windage, and stray losses. On the other hand, the *higher* the speed of the motor (up to n_{sync}), the *lower* its core losses. Therefore, these three categories of losses are sometimes lumped together and called as *rotational losses*. The total rotational losses of a motor are often considered to be constant with changing speed, since the component losses change in opposite directions with a change in speed as explained.

4.3. Torque equation – expressions for maximum torque and starting torque:

The torque developed in an Induction motor depends on the following factors.

- The stator magnetic field **φ** which induces $e.m.f$. in the rotor.
- The magnitude of the Rotor current I_{2r} in running condition.
- The power factor 'Cos Θ_{2r}' of the Rotor circuit in running condition.

Thus, the expression for Torque can be given as:

$T_a\varphi \,.\, I_{2r} \,.\, \text{Cos}\ \Theta_{2r}$ ———————————— (1)

We know that the flux φ produced by the stator is proportional to the voltage applied to the stator E_1. And similarly, the Stator and Rotor voltages E_1 and E_2 are related to each other by a ratio of their effective number of turns 'K '.

i.e., φ a E_1 and $\frac{E_1}{E_2} = K$ and so effectively φ a E_2 **-----** **(2)**

We have earlier obtained expressions for the Rotor current and Rotor power factor as:

$I_{2R} = \frac{E_{2r}}{Z_{2r}} = \frac{SE_2}{\sqrt{(R_2^2)}} + (sX_2)^2$ (at Running condition) ----- **(3)**

$\text{Cos}\ \Theta_{2R} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2}} + (SX_2)^2$ (@ Running condition) ----------- **(4)** Using the above equations at (2),(3) and (4) in equation (1) we get :

$$Ta\left[\frac{sE_2R_2}{R_2^2} + (SX_2)^2(SX_2)^2\right]$$

$$T = k\left[\frac{sE_2^2R_2}{R_2^2} + (sX_2)^2\right]$$

Where 'k' is the constant of proportionality and can be shown that $k = \frac{\mathbf{3}}{\mathbf{2\pi n_s}}$ where $\boldsymbol{n_s}$ = synchronous speed in $rps = \frac{N_S}{60}$ (Ns = Synchronous speed in RPM). Substituting this value of the constant 'k' in the above expression for Torque we get finally

$$T = \frac{3}{2\pi n_s}\left[sE_2^2\frac{R_2}{R_2^2} + (sX_2)^2\right]N - m$$

So, Torques at any load condition can be obtained if *Slip 's'* at that load and *Standstill Motor parameters* are known**.**

Starting Torque: Is the torque at the time of start in an induction motor and can be obtained by substituting the corresponding value of slip's'. At the time of starting the speed $N = 0$ and hence the slip $'s' = 1$. Using this value of 's' in the above equation for Torque we get the starting torque as:

$$T_{st} = \frac{3}{2\pi N_s}\left[E_2^2 \frac{R_2}{R_2^2} + X_2^2\right] N - m$$

4.3.1. Condition for maximum Torque:

As can be seen from the above Torque equation, the torque depends only on the slip with which the motor is running since all the other parameters are constant. Supply voltage to the stator is usually rated and hence constant and the turn's ratio between Stator and Rotor is also constant. Hence E_2 is constant. Similarly, R_2, X_2 and n_s are constants in an Induction motor. So, to find out the maximum torque we have to find out at what slip maximum torque occurs. Hence, mathematically we can write the condition for maximum Torque as $\boldsymbol{\frac{dT}{ds} = 0}$

where $T = k\ [s\ E_2^2 \frac{R_2}{\boldsymbol{R_2^2}} + (sX_2)^2]$**.** While evaluating the above differential, it is to be noted that in the above expression for Torque all the parameters like $E_2, R_2\ and\ X_2$ are also constants apart from the constant of proportionality 'k' and the only variable is $'s'$ and this term is present in both numerator and denominator. Hence, we can differentiate the expression for torque using the formula for differential of a quotient (u/v) after taking out all the constant terms out of the differential as shown below.

$$T = (kE_2^2 R_2)\left[\frac{s}{R_2^2} + s^2 X_2^2\right]$$

Now differentiating the term within the square brackets and equating the numerator alone to zero we get: So, we conclude that the torque is maximum at a slip 's' = $\frac{R_2}{X_2}$ or in other words the slip at maximum torque is given by:

$s_m = \frac{R_2}{X_2}$

4.3.2. Maximum Torque:

Now we can obtain the magnitude of maximum torque **T max** by substituting the value of '$\boldsymbol{s_m}$' $= \frac{\boldsymbol{R_2}}{\boldsymbol{X_2}}$ in place of **'s'** in the general expression for Torque.

$$T_{max} = k\left[s_m E_2^2 \frac{R_2}{\{R_2^2 + (s_m X_2)^2\}}\right]$$

$$T_{max} = k\left[\frac{R_2}{X_2}\ E_2^2 \frac{R_2}{\left\{R_2^2 + \left(\left(\frac{R_2}{X_2}\right)X_2\right)^2\right\}}\right]$$

Or finally $T_{max} = \frac{kE_2^2}{2X_2}\ N - m$

From the above expression for *Maximum Torque,* we can observe the following important points:

- It is directly proportional to the Square of the induced $e.m.f.$ E_2 in the rotor at stand still.
- It is inversely proportional to the Rotor Reactance X_2 at stand still
  - The most interesting fact is: *It is not dependent on the Rotor resistance* R_2. But the slip or speed at which such a maximum Torque occurs depends on the value of *Rotor resistance* R_2

4.3.3. Torque slip characteristic:

When an Induction motor is loaded from no load to full load its speed decreases and slip increases. Due to increased load, motor has to produce higher torque to satisfy higher load torque demand. The torque ultimately depends on the slip as we have seen earlier. The behavior of the motor can be easily analyzed by looking at the Torque versus slip curve from s=0 to 1. (Instead of Torque versus Speed Characteristics because we have readily available equations for Torque in terms of *slip 's'*. The Torque vs. Slip Characteristics can then be easily translated to Torque vs. Speed Characteristics since they are complementary to each other.)

We have already seen that for a constant supply we can rewrite the basic Torque equation $Ta\left[sE^2\frac{R_2}{R_2^2}+(sX_2^2)\right]$ is also constant.

as: $T\ a\ [s\ \frac{R_2}{R_2^2}+(sX_2^2\ )\ ]$.

To study the Torque versus Slip characteristics let us divide the slip range ($s\ =\ 0$ to 1) into $three$ parts and analyze.

The Torque speed characteristic can be divided into three important regions:

4.3.4. Low Slip Region:

In this region 's' is very small. So, the term $(sX_2)^2$ would be *small* compared to R_2^2 and hence can be neglected. Thus, $\mathrm{Tas}\frac{R_2}{R_2^2}$. i.e., Torque becomes directly proportional to slip 's'. Thus, torque increases linearly with increase in slip 's' and satisfies the load demand. Thus, we can conclude that in this region.

- The mechanical speed decreases approximately linearly with increased load
- The motor slip increases approximately linearly with increased load.
- Induced Torque increases linearly with slip thus satisfying the load demand.
- Rotor reactance is negligible. So, Rotor Power factor is almost unity.
- Rotor current increases linearly with slip.

The entire normal steady state operating range of an Induction motor lies in this linear low slip region. Thus, in normal operation, an induction motor has a linear speed drooping characteristic.

Moderate slip region: In this region:

- Rotor frequency is higher than earlier and hence the Rotor reactance is of the same order of magnitude as the rotor resistance.

- Rotor current no longer increases as rapidly as earlier and the Power factor starts dropping.
- The peak torque (Pull out or Break down Torque) occurs at a point where for an incremental increase in load the increase in the current is exactly balanced by the decrease in rotor power factor.

High slip region: In this region:

Slip is high i.e., approaching the value 1. Here it can be assumed that the term R_2^2 is very small compared to $(sX_2)^2$ .Hence the expression for Torque becomes $Tas\frac{R_2}{(sX_2)^2}$ i.e., $Ta\frac{1}{s}$. So, in high slip region Torque is inversely proportional to slip 's'**.** Hence the induced Torque decreases with increase in load torque since the increase in Rotor current is dominated by the decrease in Rotor power factor where as it should increase to meet the increase in Load demand. So, speed further comes down and Induced Torque still reduces further. So, in this process the motor comes to standstill. i.e., the motor cannot run at any point in the high slip region. Hence this region is called unstable region. On the other hand, the low slip region where the characteristic is linear is called the *stable region*.

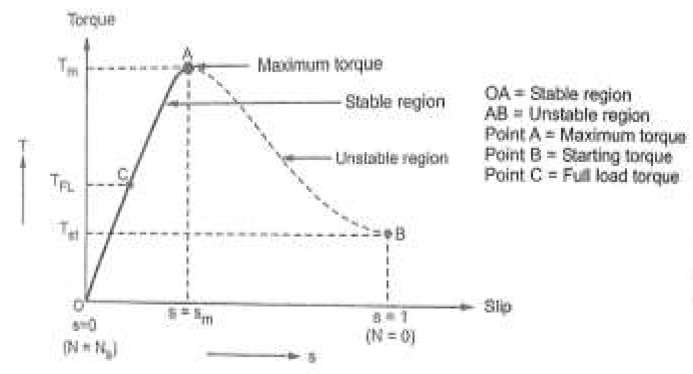


Figure 4-5. Torque-slip Characteristics (Pl change Point 'C' as Starting Torque and Point 'B' as Full Load Torque in the above figure)

The maximum Torque which the motor can produce before going into unstable region occurs at $s' = 's_m'$. Since beyond this torque the motor gets into unstable region, this maximum Torque is also called as *Break down Torque* or *pullout Torque*. The entire Torque slip characteristics are shown in the figure 4.5.

Torque vs. Speed Characteristics: Are just complimentary to the Torque-slip

Characteristics. The detailed Torque speed characteristics of an Induction Motor Showing the Starting, Pull-out and Full-load torques are shown in the figure 4-6.

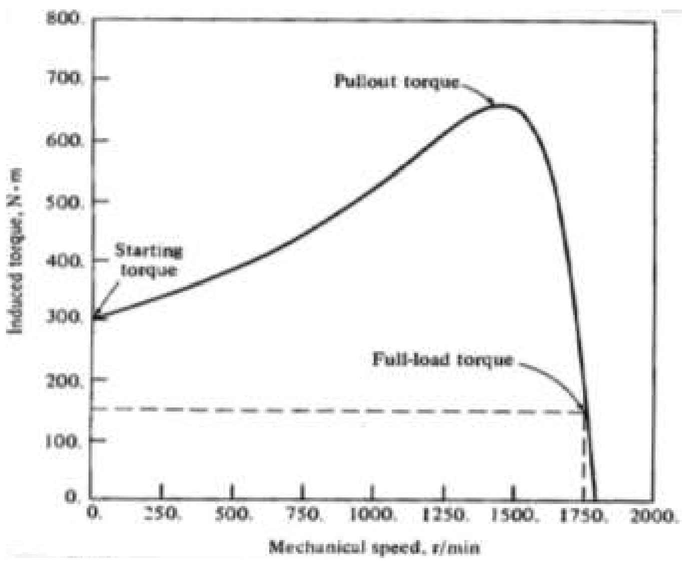


Figure 4-6. Torque speed characteristics of an Induction Motor Showing the Starting, Pull-out and Full-load torques

- Induced Torque is zero at synchronous speed.
- The graph is nearly linear between no load and full load (at near synchronous speeds). In this region the Rotor resistance is much larger than the Rotor reactance, and hence the Rotor Current, magnetic field and the induced torque increases linearly with increasing slip.
- There is a Max. Possible torque that cannot be exceeded which is known as pull out torque or breakdown torque. This is normally about two to three times the full load torque.

- The Starting torque is higher than the full load torque and is about 1.5 times. Hence this motor can start with any load that it can handle at full power.

Torque for a given slip varies as the square of the applied voltage. This fact is useful in the motor speed control with variation of Stator Voltage.

- If the rotor were driven faster than synchronous speed, then the direction of the Induced torque would reverse and the motor would work like a generator converting mechanical power to Electrical power.
- If we reverse the direction of the stator magnetic field, the direction of the induced torque in the Rotor with respect to the direction of motor rotation would reverse, would stop the motor rapidly and will try to rotate the motor in the other direction. Reversing the direction of rotation of the magnetic field is just phase reversal and this method of Braking is known Plugging.

Full load Torque: When the load on the motor Torque increases, the slip increases and thus the Induced torque also increases. The increase in induced Torque is produced by a corresponding increase in the current drawn from the supply.

The load which the motor can drive safely depends on the current which the motor can draw safely. When the current rises, the temperature rises. Hence the safe limit on the current is dictated by permissible temperature rise. *The safe limit of current is that which when drawn for continuous operation of the motor produces a temperature rise which is well within the limits.* Such a full load point is shown as point 'C' on the plot and the corresponding torque is called the Full load Torques T_{FL}. If the motor is operated beyond this full load continuously the windings' insulation is likely to be damaged. But for short durations of time the motor can be operated beyond the Full load Torque but up to the limit of *Breakdown Torque/Pull out Torque*

4.4. Speed control of Induction motors - Basic Methods: Stator side:

- Stator Voltage control
- Stator variable frequency control

Rotor side:

- Rotor resistance control
- Slip-energy recovery

Stator voltage control:

- the expression for the torque developed by an induction motor, we can see that it is directly proportional to the square of the applied terminal voltage at a constant value of supply frequency and slip. By varying the applied voltage, a set of torque-speed curves as shown below can be obtained. When the applied voltage changes by n times the resulting torque changes by n^2 times.
- If constant torque is required at different voltages, the slip increases with decreasing voltage to accommodate the required rotor current. But the power factor deteriorates at low voltages.
- Fig(b) shows the torque- speed curves along with a constant load and varying load (with speed). From this it can be seen that speed control is possible only in a limited range

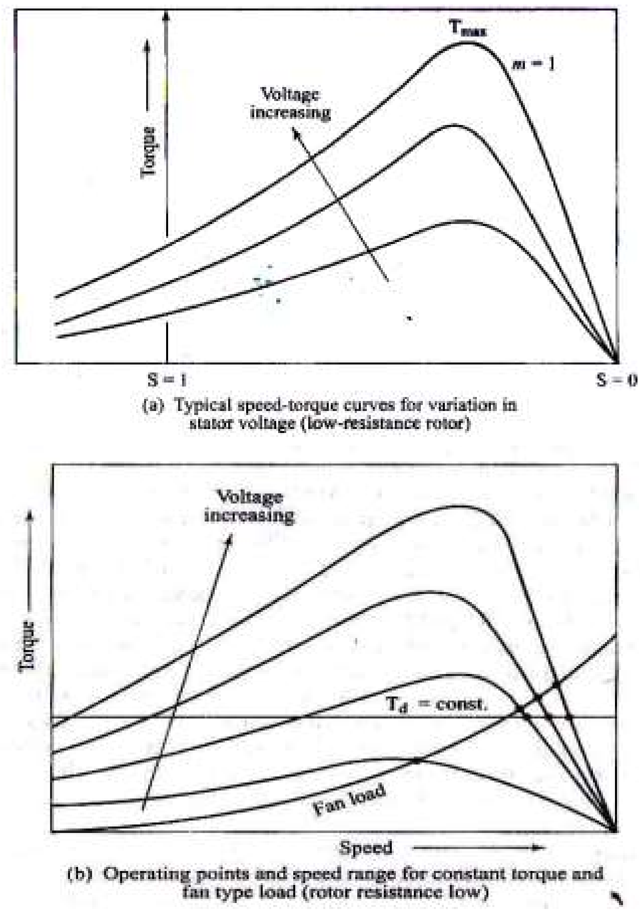


Figure 4-6. Speed control of induction motors

4.4.1. Limitations of Stator voltage control:

- The portion of the speed control beyond the maximum torque is unstable and is not suitable for speed control.
- Normal squirrel cage motors will have low rotor resistance and therefore will have a large unstable region. Hence speed control is possible only in a limited band.
- The starting current is also very high for these motors (because of low rotor resistance). Hence the equipment used for control of these motors must be able to handle/withstand such large starting currents.

- The power factor also will be poor at large slips.
- This shifts the point of slip for maximum torque to the left and decreases the unstable region.
- The unstable region can be reduced or even completely eliminated by properly designing the rotor. This increases the range of speed control substantially, reduces the starting current and improves the power factor.
- However, motors designed with high rotor resistance to achieve higher speed control range will have higher rotor losses at large slips and will have to dissipate the resulting large heat in the Rotor itself.
  - But slip ring motors allow the insertion of the high resistance externally. Hence the losses will be dissipated in the external resistors only and Rotor heating will be avoided.

4.4.2. Method of stator voltage control:

AC voltage controllers can be used for varying the applied input stator voltage. By controlling the firing angle of the thyristors connected in anti-parallel in each phase the RMS value of the stator voltage applied to each phase can be varied to get the desired speed control.

Four quadrant operations with plugging are obtained by the use of the circuit shown in the figure below. Thyristor pairs A, B and C provide operation in quadrants 1 &4 (as shown by the solid line). Thyristor pairs A', B and C' changes the phase sequence and thus provide operation in quadrants 2&3(as shown by the dotted line).

Precaution:

While changing from one set to another set of thyristor pairs, i.e. from ABC to A'BC' or *vice versa, care* should be taken to ensure that the incoming pair is activated only after the outgoing pair is fully turned off. This is to avoid short circuiting of the supply by the conducting thyristor pairs. Protection against such faults can be provided only by the fuse links and not by the current control.

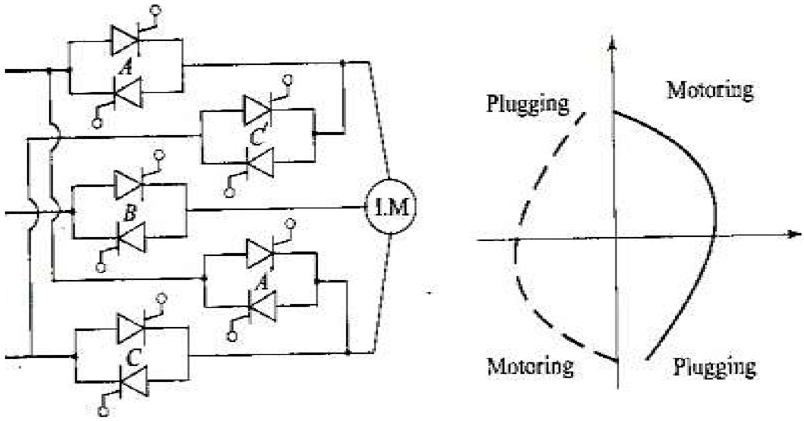


Figure 4-7. Stator voltage control

Limitations:

A review of the AC controllers reveals that:

The output voltage from an AC controller is dependent not only on the delay angle of the gate firing pulses but also on the periods of current flow which in turn are dependent on the load power factor. An induction motor will draw a varying power factor current and this will influence the voltage being applied to it. Whenever the load current is continuous, the controller will not have any influence on the circuit conditions at all.

- Control is achieved by distortion of the voltage waveforms and by the reduction of the current flow periods. Significant amounts of stator and rotor harmonic currents will flow and eddy currents will be induced in the iron core. These will cause additional motor heating and alter the motor performance compared with sinusoidal operation.

The practical results of these limitations are:

- The motor performance can be predicted only after a full understanding of the motor, thyristor converter and the load.
- A closed loop speed control based on a tachogenerator speed feedback is essential to ensure stable performance.
- The system gains most practical application when the load is predictable

and the load torque required at low speeds is relatively low.

Important formulae and equations:

- Synchronous speed of rotating magnetic field: $\boldsymbol{n_S = 120.f_S/P}$
- Voltage induced in the rotor: $\boldsymbol{e_{ind} = (v \times B)\, l}$
- Torque induced in the rotor: $\boldsymbol{T_{ind} = k.B_R \times B_S}$
- slips **o**n percentage basis:

$$s = \frac{n_{slip}}{n_{sync}} (\times 100\%)$$

$$s = \frac{n_{sync-n_m}}{n_{sync}} \times 100\%$$

Slip **s** on per unit basis: $S = \frac{N_{sync} - N_m}{N_{sync}}$

- The magnitude of the rotor induced voltage E_R in terms of the rotor induced voltage at rotor locked condition E_{R0}: $E_R = s.E_{R0}$
- The magnitude of the rotor Reactance X_R in terms of the rotor Reactance at rotor locked condition X_{R0} : $X_R = s.X_{R0}$ (since $f_r = s.f_s$ and $X_R = s.2\pi\, f_s LR$)
- The rotor frequency can be expressed as:

$$f_r = (\frac{P}{120}).(\, n_{sync} - n_m)$$

- Important relationships between Air gap power P_{AG}, converted power P_{conv}, Rotor induced Torque T_{ind}, Rotor copper losses P_{rcl} and the slip **s:**

$$T_{ind} = \frac{P_{conv}}{\omega m} = \frac{P_{AG}}{\omega s}$$

$$P_{rcl} = s.P_{AG} P_{conv} = (1 - s)P_{AG}$$

- Expressions for Torque considering Rotor circuit only:

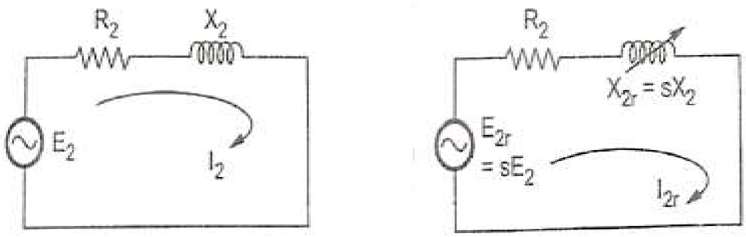


Figure 4-8. Rotor equivalent circuit (a) At standstill (b) while running

Torque developed by the motor T_d:

$$T_d = k\,[s\,E_2^2\,\frac{R_2}{R_2^2} + (sX_2)^2]$$

(Where constant $K = \frac{3}{2\pi N_s} = \frac{3}{\omega_s}$***)***

Slip at maximum Torque S_m: 's_m' $= \frac{R_2}{X_2}$

Maximum developed torque T_{max}:

$$T_{max} = \frac{kE_2^2}{2X_2}$$

Starting Torque T_{st}:

$$T_{st} = k\left[\frac{E_2^2 R_2}{R_2^2 + X_2^2}\right]$$

- Torque–Speed relations using an Equivalent circuit with both Stator and Rotor circuit parameters.

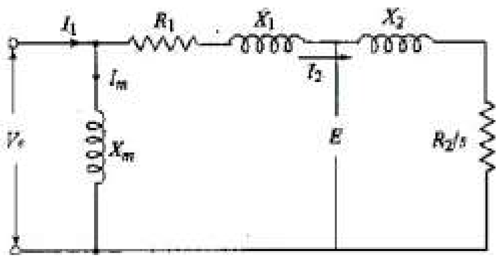


Figure 4-9. Simplified Per-phase equivalent circuit of an Induction Motor

Torque developed by the

$$T_d = \frac{P_{gross}}{\omega_r} = \frac{P_{gross}}{\omega_{s\,(1-s)}} = \frac{3V_1^2 R_2/s}{\omega_s\left[\left(R_1+\frac{R_2}{s}\right)^2+(X_1+X_2)^2\right]}$$

$$\therefore T_d = \frac{3}{\omega_s} I_2^2 \frac{R_2}{s} N - m$$

Slip at maximum Torque S_{maxT}:

$$S_{maxT} = \pm\frac{R_2}{\sqrt{R_1^2+(X_1+X_2)^2}}$$

Maximum developed torque T_{max}:

$$T_{max} = \frac{3\,V_{1ph}^2}{2\omega_s\left[R_1 \pm \sqrt{R_1^2+(X_1+X_2)^2}\right]}$$

Starting orque T_{st}:

$$T_{start} = \frac{3V_1^2 R_2}{\omega_s[(R_1+R_2)^2+(X_1+X_2)^2]}$$

Example 4-1:

A 3 kW, 400 V, 50 Hz, 4 pole, 1400 RPM, delta connected induction motor has the following parameters referred to stator. R_1 = 2.5 Ω; R_2 = 4.5 Ω; $X_1 = X_2$ = 6 Ω. Speed control is achieved by Stator Voltage Control. When driving a *fan load*, the motor runs at rated speed and rated voltage. Calculate the voltage to be applied to the motor to run at 1300 RPM.

Solution:

Given data:

V_L = 400 V, f = 50 Hz,

P =4, N_r = 1400 RPM

R_1 = 2.5 Ω;

R_2 = 4.5 Ω;

$X_1 = X_2$ = 6 Ω

Since the motor is delta connected V_L = 400 V = V_{ph}

We know that the motor synchronous speed is given by N_s = 120 f/P

= 120 x 50 /4 = 1500RPM

Hence ω_s = 1500 x2π /60 = 157 Rad/sec

Slip at the rated speed of 1400 RPM is given by s = (1500-1400)/1500 = 0.0667

Induction motor's simplified equivalent circuit taking into account both stator and rotor circuit parameters (referred to stator) is shown below.

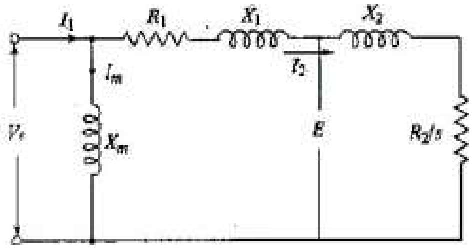


Figure 4-10 Induction motor Equivalent circuit with both Stator and Rotor circuits

From the equivalent circuit, the rotor current I_2 can be shown to be:

$$I_2 = \frac{V_{ph}}{\left[\left(R_1+\frac{R_2}{s}\right)^2+(X_1+X_2)^2\right]^{\frac{1}{2}}}$$

Substituting the values from the given data we get:

$I_2 = 400 / [\ (2.5+4.5/0.0667)^2 + (6+6)^2\ ]^{1/2}$ = 400/70.98 = 5.634 A

We know that the torque developed T_d by an Induction motor is given by:

$T_d = (3/\omega_s).\ I_2^2.\ (R_2/s)$ N-m

= $(3/157).\ (5.634)^2.\ (4.5/0.0667)$ = 40.92 N-m

[Here it may be noted that the torque developed at the rated speed was found out by first calculating the motor current using two separate formulae for current and torque. It could have been found out directly also by using the formula

$T_{d@slip\ 's'} = (3/\ \omega_s).[V^2_{ph} / \{(R_1+R_2/s)^2 + (X_1+X_2)^2\}].(R_2/s)$

We know that with a fan type of load, the load torque

$T_L\ a\ \omega_r^2\ \ and\ T_d\ = T_L$ at steady state.

From which we have

$T_d\ a\ \omega_r^2\ or\ T_d\ a\ *\omega_s\ (1-s)]^{\ 2}\quad i.e$

$T_d\ =\ \omega_s^2\ (1-s)^2\ =\ K\ (1-s)^2$

(Where K is the final constant including ω_s^2 which is also a constant since ω_s, the synchronous speed is constant)

We have the value of T_d at the rated speed of 1400 RPM (i.e., @a slip of 0.0667) and using that in the above relation $T_d = K (1-s)^2$ we can find the value of the constant K. Then using that value of K, we can use the same relation and find out the developed Torque at the required speed of 1300 RPM [i.e., @a slip of (1500-1300/1500) = 0.133]

Thus: $40.92 = K (1-0.0667)^2$ from which we get K = 46.97

And $T_{L\ @1300RPM} = K (1-s_{@\ 1300\ RPM})^2 = 46.97 \times (1-0.133)^2 = 35.28$ N-m

And we know that this is the steady state torque developed by the motor @1300 RPM which is also given by:

$T_{d@1300\ RPM} = (3/\omega_s).\ [V^2_{ph} / \{(R_1+R_2/s)^2 + (X_1+X_2)^2\}].\ (R_2/s)$

Where V_{ph} is the required phase voltage for running the motor at 1300 RPM, 's' is the corresponding slip at 1300 RPM and all other parameters are already known. Substituting these values, we get:

$35.28 = (3/157).[V^2_{ph}\ /\ \{(2.5 + 4.5/0.133)^2 + (6 + 6)^2\}].(4.5/0.133)$

$35.28 = 0.0191 \times [V^2_{\ ph}/ 1464.2] \times 33.834$ from which we get

$V^2_{\ ph} = (35.28 \times 1464.2)/ (0.0191 \times 33.834) = 79{,}936$ and $V^2\ ph = 282.72$ V

Thus, finally V_{ph} = 282.72 V is the voltage/phase to be applied to the stator windings to get a speed of 1300 RPM.

Example 4-2:

A 440 V, 3φ, 50 Hz, 6 pole, 945 RPM, delta connected induction motor has the following parameters referred to stator side. $R_1 = 2.0\ \Omega$; $R_2 = 2.0\ \Omega$; $X_1 = 3\ \Omega$, $X_2 = 4\ \Omega$. Motor speed is controlled by stator Voltage Control. When driving a fan load, the motor runs at rated speed with rated voltage. To run the motor at 800 RPM, calculate (a) torque developed by the motor (b) the voltage to be applied to the motor and (c) the corresponding current drawn.

Solution:

Given data:

$V_L = 440$ V

f = 50 Hz,

P =6, $N_r = 945$RPM

$R_1 = 2.0\ \Omega$;

$R_2 = 2.0\ \Omega$;

$X_1 = 3\ \Omega$,

$X_2 = 4\ \Omega$.

Since the motor is delta connected $V_L = 400\ V = V_{ph}$

We know that the motor synchronous speed is given by

$N_s = 120\ f/P = \ \ 120 \times 50 /6 = 1000$RPM

Hence $\omega_s = 1000 \times 2\pi /60 = 104.67$ Rad/sec

Slip at the rated speed of 945 RPM is given by s = (1000-945)/1000 = 0.055

(Refer the previous Simplified equivalent circuit of an Induction motor considering both Stator and Rotor circuits)

(a) **Torque developed to run the motor at 800 RPM:**

To find the torque developed to run the motor at 800 RPM first we have to find the torque developed at the rated speed.

From the above equivalent circuit, we know that the torque developed by the motor at rated speed is given by: (here we are finding directly by using the formula for Td@rated speed)

Td@rated speed = $(\frac{3}{\omega s}).[V_2\, p/h\, \{\left(R_1 + \frac{R_2}{s}\right)^2 \;+\; (X_1 + X_2)^2\,\}].(\frac{R_2}{s}$ rated speed)

Substituting the values from the given data we get:

$$Td@\,945\,RPM \;=\; (\frac{3}{104.67})[\frac{440^2}{\{\left(2+\frac{2}{0.055}\right)^2+(3+4)^2\,\}}](\frac{2}{0.055})$$

$$=\;(\frac{3}{104.67})\;[\frac{440^2}{\left(2+\frac{2}{0.055}\right)^2}\{+\,(3+\;4)^2\}](\frac{2}{0.055})$$

$$=(3\times 440^2\;\times 2)/\,[104.67\times\{(2\;+\;36.36)^2\;+\;(3\;+\;4)2\}\times 0.055)]$$

$$=\;(3\;\times 440^2\;\times\;2)/\,[104.67\;\times 1520.48\;\times 0.055)]\;=\;132.7\;\mathrm{N-m}$$

$$Td@\,945\,RPM\;=\;132.7\,N-m$$

We know that with a fan type of load, the load torque

$T_L a\,\omega^2 r\;\; and\; T_d \;=\;\; T_a t_L$ steady state.

From which we have

$T_d a \omega_r^2\; or\; T_d a\; *\,\omega_s\,(1-s)^2\quad i.e$

$T_d\;=\;K_s\,.\,\omega_s^2\;\,(1-s)^2\;=\;K\,(1-\;s)^2$

(Where K is the final constant including ω_s^2 which is also a constant since ω_s, the synchronous speed is constant)

We have the value of T_d at the rated speed of 945 RPM (i.e., @a slip of 0.055) and using that in the above relation T_d=K $(1\text{-s})^2$ we can find out the value of the constant K. Then using that value of K, we can use the same relation and find out the developed Torque at the required speed of 800 RPM [i.e., @a slip of (1000-800/1000) = 0.2

Thus: 132.7 = K $(1\text{-}0.055)^2$ from which we get K = 148.6

$T_{L\;@800RPM}$ = K $(1\text{-}s_{@\;800\;RPM})^2$ = 148.6 x $(1\text{-}0.2)^2$ = 95.1 N-m

And we know that this is the steady state torque developed by the motor @800 RPM and hence:

Torque developed by the motor @800 RPM = 95.1 N-m

(b) Voltage to be applied to the stator to run the motor at 800 RPM:

From the above equivalent circuit, we know that the per phase voltage V_{ph} to be applied to the stator in terms of the steady state torque developed by the motor @800 RPM is given by:

$$\mathbf{Td@800\ RPM} = (\frac{3}{\omega s}).[V^2ph\ /\{\left(R_1 + \frac{R_2}{s}\right)^2 + (X_1 + X_2)^2\}].(\frac{R_2}{s}@800\ RPM)$$

where ‘s’ is the corresponding slip at 800 RPM and all other parameters are already known. Substituting these values, we get:

$$95.1 = (\frac{3}{104.67})[V^2ph/\{\left(2 + \frac{2}{0.2}\right)^2 + (3 + 4)^2\}](\frac{2}{0.2})$$

$$95.1 = (\frac{3}{104.67})[\frac{10V^2ph}{144 + 49}]$$

From which $V^2ph = 95.1 \times 104.67 \times \frac{193}{30} = 64056.5$

And thus, finally $V_{ph} = \sqrt{64056.5} = 253.09V$is the voltage/phase to be applied to the stator windings to get a speed of 800 RPM.

(c) Current drawn by the motor to run the motor at 800 RPM:

From the above equivalent circuit, we also know that the Torque developed, current drawn and the slip at any speed are related by:

$$\boldsymbol{T_d = \left(\frac{3}{\omega_s}\right).I_2^2.\left(\frac{R_2}{s}\right) i.e. I_2^2 = T_d\,.\omega_s.\frac{s}{3R_2}}$$

Substituting the values, we have for the RHS expression we get

$$I_2^2 = 95.1 \times 104.67 \times \frac{0.2}{3} \times 2 = 331.8039\ and$$

$$I_2 = 331.8039 = 18.21\ A$$

But since the motor is delta wound the input current is to be taken as line current and hence:

$$I_{2L} = \sqrt{3} \times I_2 = \sqrt{3} \times 18.21 = 31.54A$$

Current drawn by the motor to run at 800 RPM = 31.54 A

4.5. Variable frequency control:

4.5.1. Speed control By Change of frequency:

The synchronous speed is given by $N_S = 120\ f/P$. Thus, by controlling the supply frequency smoothly, the synchronous speed can be controlled over a wide speed range. But form the basic transformer voltage equation we have the expression for the air gap flux:

$$V = [4.44\ K_1\ \Phi\ T_{ph} f]$$

from which

$$\Phi = [\frac{1}{4.44}\ K_1\ T_{ph}]\ (\frac{V}{f})$$

Where:

K_1 = Stator winding constant,
T_{ph1} = Stator turns /phase,
V =Supply voltage and
f = Supply frequency

From the above expression it can be seen that if the frequency is reduced the flux will increase which results in saturation of the stator and rotor magnetic cores. This saturation in turn results in increase in magnetization current (no load current) which is undesirable. Hence it is required to maintain the air gap flux constant when supply frequency is changed. From the above expression for flux Φ we can see that this can be achieved by changing the Voltage also correspondingly so as to maintain a constant V/f ratio. Hence with V/f control method which ensures constant flux Φ, we can get smooth speed control.

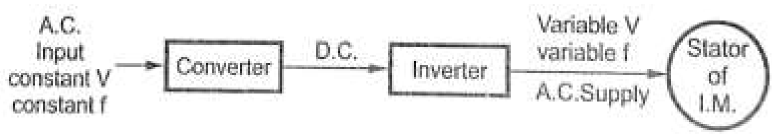


Figure 4-11. Electronic V/f control scheme

Such a constant $\frac{V}{f}$ with both variable voltage and frequency can be obtained using an electronic converter and an inverter as shown in the figure below.

The converter converts the normal input power supply into DC. The inverter then converts the DC supply into a variable frequency supply as per the speed required but maintaining a constant $\frac{V}{f}$. If f_1 is the nominal frequency, then the figure below shows the Torque – slip characteristics with frequency $f_5 < f_4 < f_3 < f_2 < f_1$

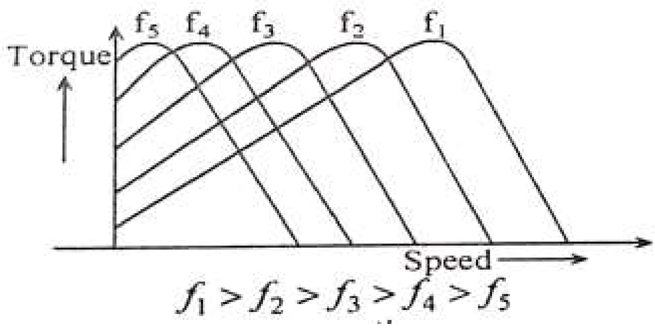


Figure 4-12. Torque – Speed Characteristics with variable f and constant V/f

4.6. Control of Induction Motors by Voltage Source Inverters:

An Inverter belongs to the VSI category if looking from the load side the AC terminals of the Inverter function as a Voltage Source. A voltage source has very ***low*** internal Impedance and the terminal voltage remains substantially constant with variations in load. Hence it is suitable for both single motor and multi motor drives. Any short circuit across its terminals causes current to rise very fast due to low internal impedance. The fault current cannot be regulated by current control and must be cleared by fast acting fuse links.

In a Voltage source Inverter, the DC source is connected to the Inverter through a series Inductor **Ls** and a parallel capacitor **C**. The capacitance of **C** is sufficiently large that the Voltage would almost be constant. The output voltage waveform would be roughly a square wave since voltage is constant and the output current waveform would be approximately triangular. Voltage variations will be small but current can vary widely with variations in load.

The figure below shows the circuit diagram of a VSI employing transistors. Any other self-commutating device can also be used instead of transistors. Generally, MOSFETs are used in low voltage and low power inverters. IGBTs and power transistors are used up to medium power levels. GTOs and IGCTs (**I**nsulated **G**ate **C**ommutated **T**hyristors) are used for high power levels.

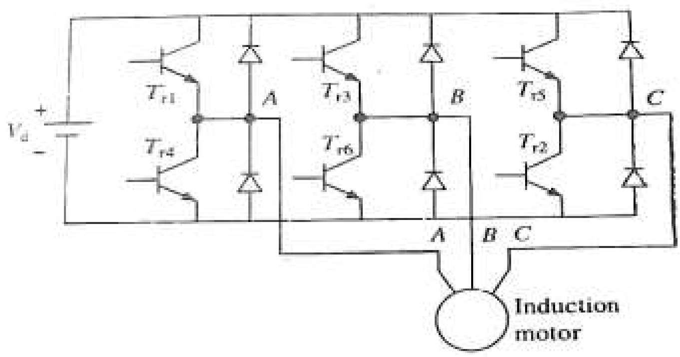


Figure 4-13. Circuit Diagram of a Transistor based Three Phase Voltage Source Inverter

VSI can be operated as a stepped wave Inverter or a PWM Inverter. When operated as a stepped wave Inverter, transistors are switched in the sequence of their numbers with a time difference of T/6 and each transistor is kept ON for a period of T/2. The resultant line voltage is shown in the figure (b) below. Frequency of operation is varied by varying the time period T and the output voltage of the inverter is varied by varying the DC input voltage.

The limitations of low frequency operation in Stepped wave Inverter can be eliminated in a PWM inverter by obtaining voltage control in the inverter itself. The inverter is supplied with a constant DC voltage and the inverter is controlled so that the average voltage is variable. In this method the operation of the inverter can be extended up to zero frequency as the commutation is effective at all frequencies.

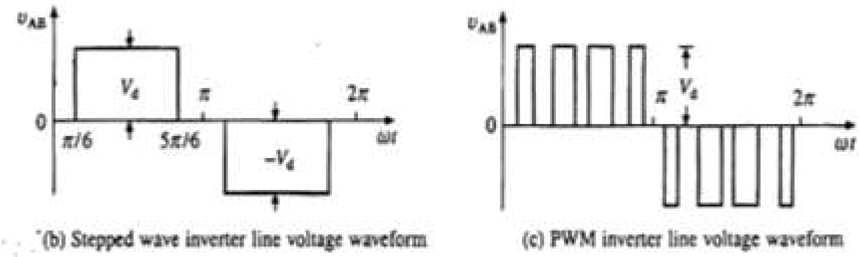


Figure 4-14. Stepped wave and PWM Inverter waveforms

In PWM the output voltage is no longer a square wave but a pulsed wave. This method results in a pure sinusoidal output if sinusoidal modulation is used. The output voltage waveform is shown in the figure (c) below.

The speed of an induction motor can be controlled using a DC or an AC source and four typical schemes of VSIs are shown and explained below with the figure shown below.

- The controlled rectifier varies the DC voltage to the inverter at the same time as the inverter output frequency is varied. The section between the DC source and the Inverter is known as the DC link and it includes a series Inductance and large capacitance which smoothes the DC voltage to an almost constant value, E_{DC}. In this if the inverter is a six step Inverter the motor voltage is controlled by adjusting the DC link voltage.
- The above system cannot regenerate since current flow cannot be reversed. If regeneration is required it can be obtained by replacing the phase-controlled rectifier with a Dual Converter as shown in figure **(b).**
- A system in which the DC link voltage is constant is shown figure **(c).** In this scheme the Inverter is a PWM based system and it varies both the voltage and the frequency.
- In the fourth scheme the variation of voltage is obtained by a chopper. Due to the chopper the harmonic injection into the AC supply is reduced.

This scheme is a combination that is used when a high frequency output is required and hence a PWM inverter is not possible.

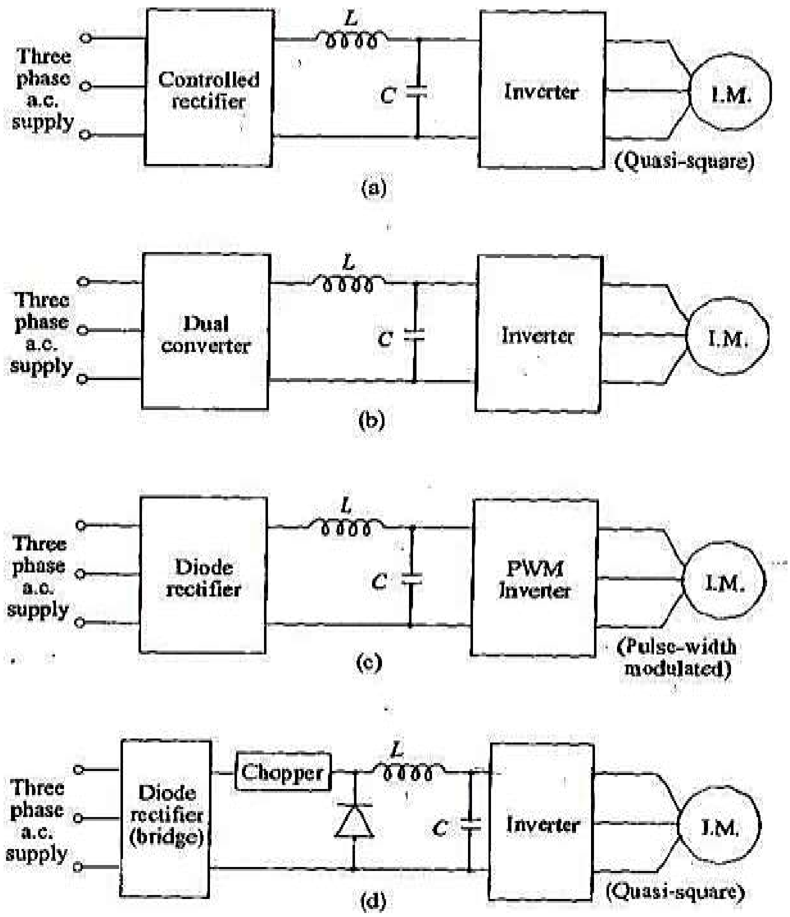


Figure 4-15. Schemes for Induction Motor speed control by VSIs

4.7. Control of Induction Motors by Current Source Inverter

An Inverter belongs to the CSI category if looking from the load side the AC terminals of the Inverter function as a Current Source. A current source has *large* internal Impedance and hence the terminal voltage of a CSI changes substantially with change in load. If used in a multi motor drive a change in load would affect the other motor drives and hence a CSI is not suitable for multi motor drives. But since the inverter current is independent of load impedance it has inherent protection against short circuits across its terminals.

In a Current Source Inverter, the DC source is connected to the Inverter through a large series Inductor L_S which would limit the current to be almost constant. The output current waveform would roughly be a square wave since current is constant and the output voltage would be approximately triangular. It is easy to limit the over current conditions in this system but the output voltage can swing widely in response to changes in load conditions.

A thyristor based **C**urrent **S**ource **I**nverter (CSI) is shown in the figure (a) below. This is a stepped wave inverter whose operation is already explained. Diodes $D1 - D6$ and capacitors C1-C6Type equation here. provide commutation of thyristors $T1 - T6$ which are fired with a phase difference of 60° in sequence of their numbers. Figure (b) below shows the nature of output current waveforms. The inverter behaves as a current source inverter due to the presence of the large Inductor in the DC link.

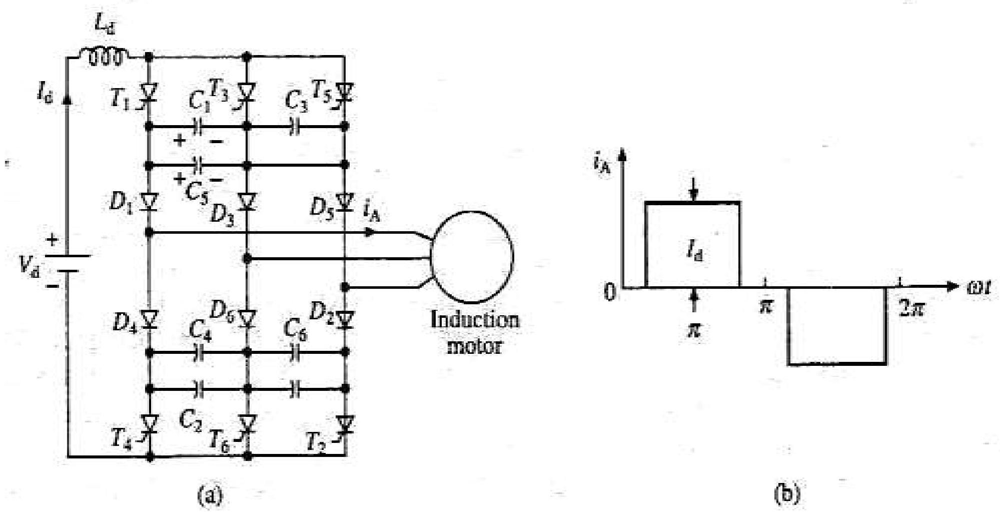


Figure 4-16. (a) Circuit diagram of a Current Source Inverter (b) Current waveform

The fundamental component of motor phase current from figure (b) is given by

$$I_s = \left(\sqrt{\frac{6}{\pi}}\right) I_d$$

For a given speed, torque is controlled by varying the DC link current I_d by changing the value of V_d . Hence when supply is AC, a controlled rectifier is connected between the supply and Inverter. When the supply is DC, a chopper is connected between the supply and Inverter as shown in the figure (b) below. The maximum value of DC output voltage of the fully controlled rectifier and chopper are chosen such that the motor terminal voltage saturates at rated value.

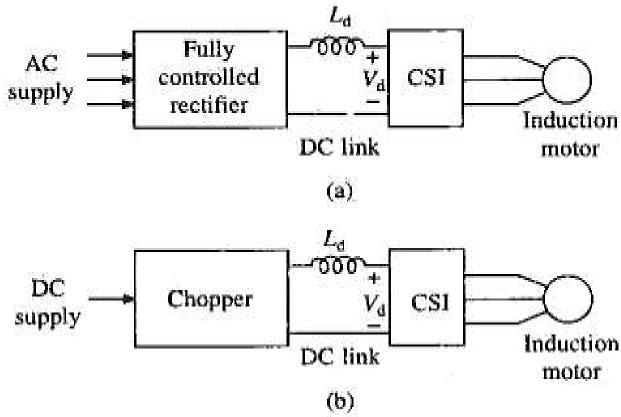
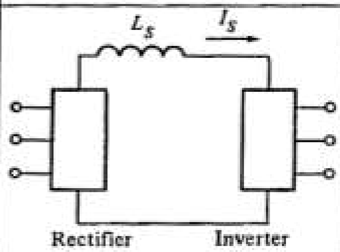
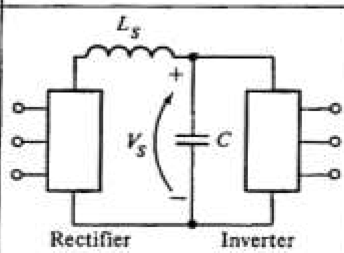
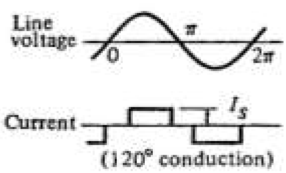
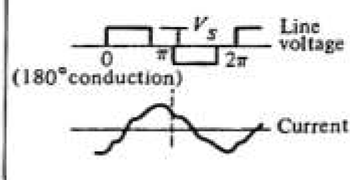


Figure 4-17. Different configurations of CSI Induction motor drives.

4.7.1. Comparison of $VSIs$ with $CSIs$:

	Current source inverter	Voltage source inverter
Main circuit configuration		
Type of source	Current source – I_s almost constant	Voltage source – V_s almost constant
Output impedance	High	Low
Output waveform		
Characteristics	1. Easy to control overcurrent conditions with this design 2. Output voltage varies widely with changes in load	1. Difficult to limit current due to capacitor 2. Output voltage variations small due to capacitor

- The major advantage of CSI is its reliability. In case of $VSIs$ a commutation failure would cause the switching devices in the same leg to conduct simultaneously. This causes a shorting of the source voltage and hence the current through the devices would rise to very high levels. Expensive high speed semiconductor fuses are required to be used to protect the devices.
- In case of $CSIs$ simultaneous conduction of two devices in the same leg will not lead to sudden rise of current due to the presence of the large Inductance. This allows time for commutation to take place and normal

operation will get restored in the subsequent cycles. Further less expensive HRC fuses are good enough for protection of thyristors.

- As seen in the CSI current waveforms, the motor current rise and fall are very fast. Such a fast rise and fall of current through the motor leakage Inductance of the motor produces large voltage spikes. Therefore, a motor with low leakage reactance is used. Even then voltage spikes could be large. The commutation capacitors $C1 - C6$ reduce the voltage spikes to some extent by limiting the rise and fall of current. But large values of capacitors are required to substantially reduce the voltage spikes. Large values of commutation capacitors have the advantage that cheap converter grade thyristors can be used but then they reduce the frequency range of the inverter and hence the speed range of the drive.
- Further, due to large values of Inductors and capacitors, the CSI drive is expensive *and will have more weight and volume.*

4.8. Cycloconverter:

A cycloconverter is a type of AC-to-AC converter that directly converts AC power of one frequency to AC power of another, typically lower, adjustable frequency, without an intermediate DC link. This unique capability makes them particularly suitable for certain electrical drive applications.

4.8.1. How they work:

- **Direct Conversion:** Unlike conventional AC-DC-AC converters (which rectify AC to DC, then invert DC back to AC), cycloconverters directly synthesize the output AC waveform from segments of the input AC supply.
- **Thyristor-based:** They primarily use phase-controlled power semiconductor switches, such as thyristors (SCRs), arranged in positive and negative converter groups.
- **Waveform Synthesis:** By carefully controlling the firing angles of these

thyristors, the cycloconverter selects and combines portions of the input AC waveform to create an output waveform with the desired voltage and frequency.

- **Step-down operation:** Most commonly, cycloconverters operate in "step-down" mode, meaning the output frequency is lower than the input frequency (e.g., typically up to 1/2 or 1/3 of the input frequency for good waveform quality). Step-up cycloconverters (output frequency higher than input) are less common due to complexity.
- **Four-Quadrant Operation:** Cycloconverters can provide four-quadrant operation, meaning they can control both the direction of torque and speed, allowing for motoring and regenerative braking.

4.8.2. Key Characteristics in Electrical Drives:

- **Variable Speed Control:** They provide smooth and continuous speed control of AC motors by varying the output frequency and voltage.
- **High Power Applications:** Cycloconverters are often used in very high-power applications, ranging from megawatts to tens of megawatts.
- **Direct AC-AC Conversion:** Eliminating the intermediate DC link means fewer components (no large filter inductors or capacitors) and potentially higher efficiency in some scenarios.
- **Natural Commutation:** In step-down cycloconverters, thyristors can often be naturally commutated by the AC supply voltage, simplifying the control compared to forced commutation required in some other converters.
- **Harmonics:** Cycloconverters inherently produce harmonics in their output waveform, which can affect motor performance and require consideration in system design. However, the leakage inductance of the motor itself can help filter some of these harmonics.

4.8.3. Applications in Electrical Drives:

Cycloconverters are especially well-suited for heavy-duty, low-speed, and high-power AC motor drives where precise speed and torque control, as well as regenerative braking, are essential. Common applications include:

- **Rolling Mills:** Used for precise speed control of large motors in steel and metal processing to ensure consistent product quality.
- **Mine Hoists:** Providing smooth and controlled acceleration, deceleration, and braking for heavy loads in mining operations.
- **Cement Kilns and Ball Mills:** Enabling the starting of large, fully loaded motors at very slow speeds and gradually bringing them up to full speed, which is crucial for these heavy industrial processes.
- **Ship Propulsion Systems:** Offering variable speed control for large marine propulsion motors.
- **Scherbius Drives:** Used with wound-rotor induction motors for slip power recovery, improving efficiency.
- **Electric Traction:** Historically used in electric locomotives to provide variable frequency power from fixed frequency AC lines.
- **Synchronous Motor Drives:** Particularly advantageous for large synchronous motors due to their ability to supply lagging, leading, or unity power factor loads while the input is always lagging.

4.8.4. Advantages:

- **Direct AC-AC Conversion:** No intermediate DC link, leading to a potentially simpler and more efficient power circuit for certain applications.
- **Four-Quadrant Operation:** Allows for both motoring and regenerative braking, offering excellent control over the drive system.
- **Smooth Low-Speed Operation:** Can achieve very low output frequencies (down to zero), enabling smooth starting and operation of

large motors under full load.

- **Robustness:** Often use robust thyristor devices.
- **Less Maintenance:** For AC motors, cycloconverter drives eliminate brushes, commutators, and slip rings associated with DC motor drives, leading to reduced maintenance.

4.8.5. Disadvantages:

- **Limited Output Frequency Range:** Typically limited to output frequencies lower than the input frequency (e.g., 1/2 or 1/3 of input frequency).
- **Harmonic Distortion:** Produce significant harmonics in both input and output waveforms, requiring filtering or careful design to mitigate their effects.
- **Complex Control:** The control circuitry for cycloconverters can be more complex due to the precise firing angle control required for multiple thyristors.
- **Size and Cost:** Can be bulky and expensive, especially for higher power ratings due to the large number of thyristors required.
- **Poor Input Power Factor:** Tend to operate at a lagging power factor, especially at light loads.

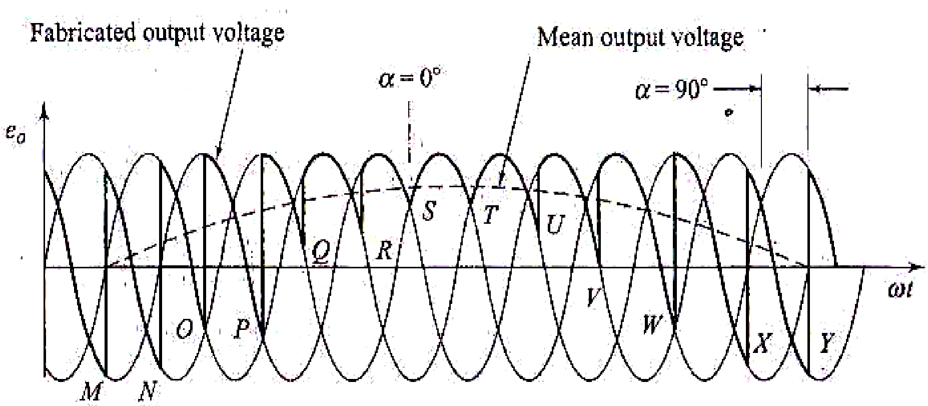


Figure 4-18. Fabricated and mean output voltage waveform for a single phase Cycloconverter (half cycle)

Cycloconverter is a device for directly converting AC power at one frequency to AC power at another frequency. The input to cycloconverter is a three-phase source which consists of three AC voltages equal in magnitude and phase shifted from each other by $120°$. The output is the desired frequency at the required voltage and power level.

As we know, in a three-phase full converter the mean output DC voltage is maximum with a firing angle of 0° and is zero with a firing angle of 90° and is negative maximum with a firing angle of 180°. In between it varies from

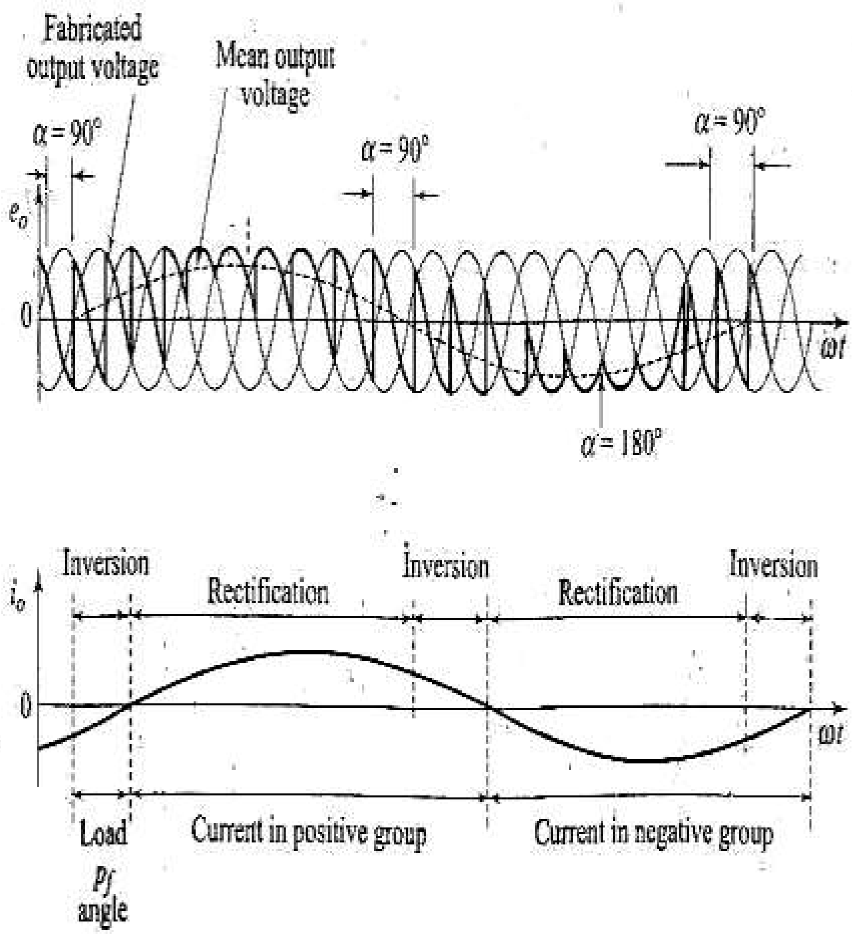


Figure 4-19. Fabricated and mean output voltage waveform for a single phase

4.9. Cycloconverter (full cycle)

positive maximum to negative maximum with corresponding firing angle variation. Cycloconverter makes use of this basic principle and generates its output voltage by selecting the combination of the three phases which are made to closely approximate the desired single-phase output by varying the firing angle continuously in accordance with a control signal. The control signal is the low-level frequency of the desired output.

The synthesized (fabricated) output voltage from the three phases along with the corresponding desired mean output voltage for half cycle and full cycle for one phase are shown in the figure below.

A full three phase Cycloconverter is made up of three such cycloconverters connected together as shown in the figure below utilizing half wave converters connected in anti-parallel in a circulating current mode as shown in the subsequent figures below.

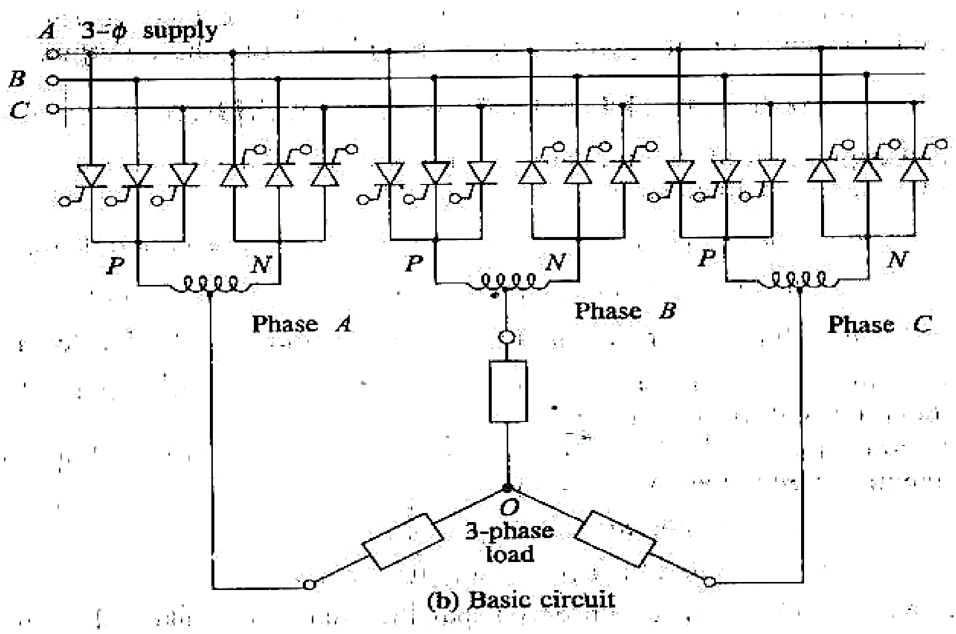


Figure 4-20. Three **phases** to Three phase Cycloconverter basic circuit diagram

4.9.1. Closed loop speed control with VSI/Cycloconverter based Induction Motor drives:

A closed loop speed control system is shown in the figure below. It employs a slip speed inner loop and an outer speed loop. Since for a given slip speed, current and Torque are constant, slip speed inner loop is used in place of inner current loop. Further it ensures that speed of operation is always on that portion of the Speed Torque curve between synchronous speed and the speed at maximum Torque for all frequencies. This ensures high Torque to current ratio. The drive shown here uses a PWM inverter fed from a DC source which has capability for regenerative braking and four quadrant operations. This scheme is applicable to any of the VSI or Cycloconverter drives as well which has Regenerative or dynamic braking capability. The closed loop operation is explained below.

The speed error is processed through a PI controller and a slip regulator. PI controller is used to get good steady state accuracy. The slip regulator sets the slip speed command $\omega \times sl$ whose maximum value is limited to limit the inverter current to a permissible value. The synchronous speed obtained by adding actual speed ω_m and slip speed $\omega \times sl$ determines the inverter frequency. The reference signal for the closed loop control of the machine terminal voltage V^* is generated from frequency f using a function generator which ensures a constant flux operation up to base speed and operation at constant terminal voltage above base speed.

A step increases in speed command $\omega \times m$ produces a positive speed error. The slip speed command $\omega \times sl$ is set to the maximum positive value. The drive accelerates at the maximum permissible inverter current producing maximum available torque until the speed error is reduced to a small value. The drive finally settles at a slip speed for which the motor torque balances the load torque.

A step decreases in speed command $\omega \times m$ produces a negative speed error. The slip speed command $\omega \times sl$ is set to the maximum negative value. The drive decelerates under regenerative braking at the maximum permissible inverter current producing maximum available braking torque until the speed error is reduced to a small value. The drive finally settles at a slip speed for which the motor torque balances the load torque.

With this scheme the drive has fast response because the speed error is corrected at the maximum available torque. Direct control of slip assures stable operation under all operating conditions.

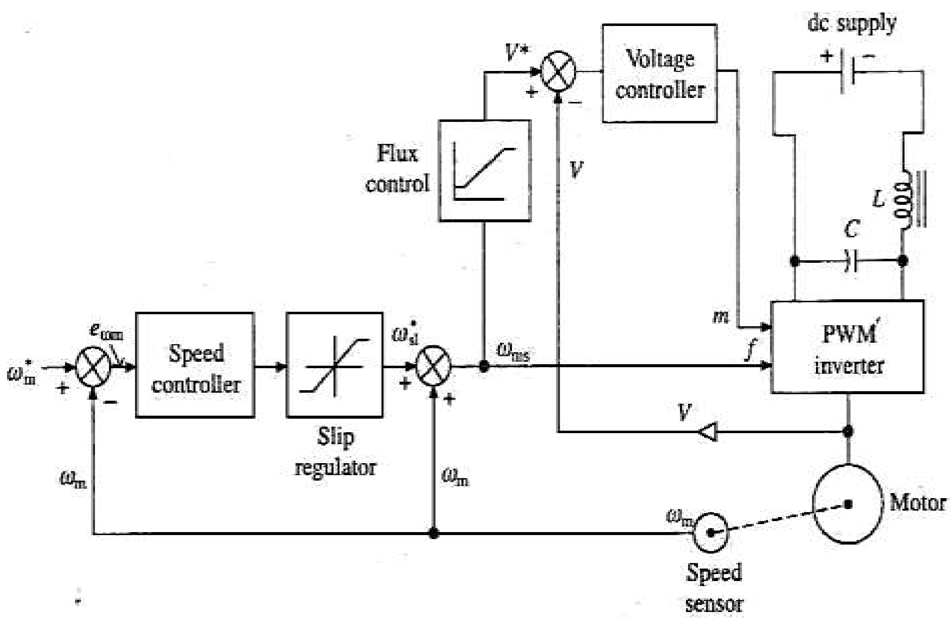


Figure 4-21. Closed loop slips controlled *VSI* Induction motor drive with *PWM* inverter.

Summary:

- Synchronous speed of an induction motor is directly proportional to the supply frequency. Hence by changing the supply frequency the synchronous speed and hence the motor speed can be varied.
- The motor terminal voltage is proportional to the product of the frequency and the flux neglecting the stator voltage drop as given by the relation: $v(t)\alpha\omega.\varphi$. Hence any reduction in the supply frequency without a corresponding reduction in the Stator voltage would cause an increase in the air gap flux and a corresponding increase in the magnetization current which is not desirable.

- Hence to avoid excessive magnetization currents and also to maintain the torque constant, variable frequency control below the base speed is normally carried out by reducing the stator voltage along with frequency in such a manner that magnetic flux is maintained constant. This method is called constant $\frac{V}{f}$ control. But above the base speed, the stator voltage is maintained constant because of the limit imposed by the stator insulation or by supply voltage limitations and hence the developed torque would come down.
- The two important systems of Induction motor speed control using variable frequency are **V**oltage **S**ource **I**nverters (VSI) and **C**urrent **S**ource **I**nverters (CSI).
- The important type of Inverters used in these systems are Quasi Square Wave Inverters (QSW), Pulse Width Modulated Inverters (PWM) and Cycloconverters.

Example 4-3:

$A\ 3\varphi, 415\ V, 50\ Hz, 4\ pole, 1460\ RPM$, star connected induction motor has the following parameters. $R_1 = 0.65\ \Omega$; $R_2 = 0.35\Omega$; $X_1 = 0.95\ \Omega, X_2 = 1.43\ \Omega, X_m = 28\ \Omega$. Motor speed is controlled by varying stator Voltage and frequency keeping the $\frac{V}{f}$ ratio constant at the rated condition. Determine the maximum Torque and speed at which it occurs for stator frequencies (a) $50\ Hz$ (b) $35\ Hz$ (c) $10\ Hz$.

Solution:

Given data:

$V_L = 415\ V$

$f = 50\ Hz$

$P = 4$

$N_r = 1460\ RPM$, Stator STAR connected and

$R_1 \ = \ 0.65\,\Omega;$

$R_2 \ = \ 0.35\Omega;$

$X_1 \ = \ 0.95\,\Omega,$

$X_2 \ = \ 1.43\,\Omega,$

$X_m \ = \ 28\,\Omega$

To understand how to work out the problem, the following points are to be noted first:

- It is not mentioned whether the rotor parameters R and X are referred to stator. But we know that in the equivalent circuit and in the corresponding formulae they are normally considered to be referred to stator. Since the stator/rotor turns ratio is required for calculating stator referred parameters and it is not given we can assume that the given rotor parameters are referred to stator.
- Since the stator is connected in STAR, the given stator voltage of 415 V is line voltage. Hence: $V_{ph} \ = \ 415\ /\sqrt{3} \ = \ 239.6\,V$
- The given reactance parameter values X_1 and $X_{2,}$ (which are frequency dependent) though not mentioned specifically, we can always take them to be at the rated frequency of 50 Hz. Their values at the other required frequencies of 35 Hz and 10 Hz are to be scaled down correspondingly.
- It is important to note that for the two lower frequencies the applied voltage V_{ph} is to be scaled down correspondingly so as to maintain constant V/f as specified in the problem.
- The synchronous speed for the two lower frequencies is also to be scaled down.
- Then, using these values appropriately, the maximum Torque and the speed at which it occurs for stator frequencies (a) 50 Hz (b) 35 Hz (c) 10 Hz. can be found one by one using the following formulae. (The formula for 'Slip @ maximum Torque' is also given below since it is required to find out the 'Speed @maximum Torque'

The slip @maximum torque, the speed @maximum torque and the maximum torque are given by:

- Slip @ maximum Torque: $S_m = \frac{R_2}{[R_1^2+(X_1+X_2)^2]^{\frac{1}{2}}}$
- Speed @maximum Torque: $N_r @ max\tau = N_s(1 - S_m)$
- Maximum Torque:

$$T_{d\,max} = \frac{3V_{ph}^2}{2\omega_s\left[R_1+\{R_1^2+(X_1+X_2)^2\}^{\frac{1}{2}}\right]}$$

Now, substituting the corresponding values from the above data we can find out the above three for the three frequencies.

50 Hz:

Synchronous speed $(RPM): N_s = \frac{120f}{P} = 120 \times 50 /4 = 1500\ RPM$

Synchronous speed (Rad/sec): $\omega_s = 1500 \times \frac{2\pi}{60} = 157\ Rad/sec$

Slip @ maximum Torque: $s_m = \frac{0.35}{[0.65^2 + (0.95+1.43)^2]}\frac{1}{2} = 0.142$

Speed @max Torque: $\mathrm{N_r = N_s\ (1 - S_m) = 1500\ (1 - 0.142) = 1287\ RPM}$

Maximum torque:

$$T_{dmax} = 3x239.6^2/2 \times 157[0.65 + \{0.65 \times 3^2 + (0.95 + 1.43)^2\}^{\frac{1}{2}}]$$

$T_{dmax} = 175.96\ N - m$

35 Hz:

Synchronous speed (RPM): $N_s = \frac{120f}{P} = 120 \times \frac{35}{4} = 1050\ RPM$

Synchronous speed (Rad/sec): $\omega_s = 1050 \times \frac{2\pi}{60} = 109.95\ Rad/sec$ R_1 and R_1 remain same.

But $X_1 = 0.95 \times \frac{35}{50} = 0.665\ \Omega\ and\ X_2 = 1.43 \times \frac{35}{50} = 1.0\ \Omega$

$V_{ph} = 239.6 \times \frac{35}{50} = 167.72\ V$

Slip @ maximum Torque: $s_m = \frac{0.35}{[0.65^2 + (0.665+1.0)^2]^{\frac{1}{2}}} = 0.1957$

Speed @max Torque:

$N_r = N_s\,(1 - s_m) = 1050\,(1 - 0.1957) = 844.515\ RPM$

Maximum torque:

$T_{dmax} = 3 \times 167.72^2 \times 2 \times 109.95\ \left[0.65 + \{0.65^2 + (0.665 + 1)^2\}^{\frac{1}{2}}\right] = \frac{84389.99}{219.9} = 157.38\ N - m$

10 Hz:

Synchronous speed (RPM): $N_s = 120f/P = 120 \times 10/4 = 300$ RPM Synchronous speed (Rad/sec): $\omega_s = 300 \times \frac{2\pi}{60} = 31.4$ Rad/sec R_1 and R_2 remain same. But $X_1 = 0.95 \times \frac{10}{50} = 0.19\ \Omega$ and $X_2 = 1.43 \times \frac{10}{50} = 0.286\ \Omega$

$V_{ph} = 239.6 \times 10/50 = 47.92\ V$

Slip @ maximum Torque:

$S_m = \frac{0.35}{[0.65^2 + (0.19+0.286)^2]^{\frac{1}{2}}} = \frac{0.35}{0.8056} = 0.434$

Speed @max Torque:

$N_r = N_s\,(1 - S_m = 300\,(1 - 0.434) = 169.8\ RPM$

Maximum torque:

$T_{dmax} = 3 \times 47.92^2 / 2 \times 31.4\,[0.65 + \{0.65^2 + (0.19 + 0.286)^2\}^{\frac{1}{2}}]$

$= 6888.979/62.8\,(0.65 + 0.805) = 75.37 N - m$

Example 4-4.

For a 3-phase delta connected 6-pole $50\ Hz\ 400\ V, 925\ rpm$ squirrel cage induction motor is having $R_s = 0.2\ \Omega, R_r = 0.3\Omega, X_s = 0.5, and\ X_r =$

$1.1\ \Omega$. The motor is operated from a voltage source inverter with constant V/f ratio from $0\ to\ 50\ Hz$ and having the constant voltage of $400\ V$ above $50\ Hz$ frequency. Calculate (i) speed for a frequency of 35 Hz with half full load torque (ii) torque for a frequency of $35\ Hz$ for a speed of $650\ rpm$.

Solution:

Given data:

$V_L\ =\ 400\ V$

$f\ =\ 50\ Hz$

$P\ = 6$

$N_r\ =\ 925\ RPM$, Stator DELTA connected and

$R_1\ =\ 0.2\ \Omega;$

$R_2\ =\ 0.3\Omega;$

$X_1\ =\ 0.5\ \Omega,$

$X_2\ =\ 1.1\ \Omega$

The following points are to be noted first:

- It is not mentioned whether the rotor parameters R and X are referred to stator. But we know that in the equivalent circuit and in the corresponding formulae they are considered to be referred to stator. Since the stator/rotor turns ratio is required for calculating stator referred parameters and it is not given we can assume that *the given rotor parameters are referred to stator.*
- Since the stator is connected in DELTA, the given stator voltage of 400 V is line voltage as well as Phase voltage. Hence: $V_{ph}\ =\ 400\ V$
- The given reactance parameter values X_1 and X_2, (which are frequency dependent) though not mentioned specifically, we can always take them to be at the rated frequency of 50 Hz. Their values at the other required frequency of 35 Hz are to be scaled down correspondingly.
- It is important to note that for the lower frequency of 35 Hz the applied

voltage V_{ph} is also to be scaled down correspondingly so as to maintain constant V/f as specified in the problem.

- Calculation of speed for a frequency of 35 Hz with half full load torque: We have the standard relation for the Torque developed in an Induction motor as:

$$T_d = \frac{\left(3V_{ph}^2 . \frac{R_2}{s}\right)}{\omega_s \left[\left(R_1 + \frac{R_2}{s}\right)^2 + (X_1 + X_2)^2\right]}$$

A close observation of this equation indicates that:

- If we can first find out 'half full load torque' then we can find out the slip @35 Hz and then we can get the speed corresponding to a frequency of 35 Hz with half full load torque.
- And full load torque can be found out by using the same relation with data corresponding to the full load condition. (Same as rated values)

Calculation of Full load (rated) Torque:

Synchronous speed (RPM):

$$N_s = \frac{120f}{P} = 120 \times \frac{50}{6} = 1000\ RPM$$

Synchronous speed (Rad/sec):

$$\omega_s = 1000 \times \frac{2\pi}{60} = 104.7\ Rad/sec$$

$$Slip\ 's'\ @\ full\ load = \frac{1000 - 925}{1000} = 0.075$$

Now using these values along with the given data in the above equation for the developed torque we can find out the Full load Torque.

$$R_1 = 0.2\,\Omega;\ R_2 = 0.3\Omega;\ X_1 = 0.5\,\Omega, X_2 = 1.1\,\Omega$$

$$T_d = \frac{\left(3V_{ph}^2 . \frac{R_2}{s}\right)}{\omega_s\left[\left(R_1+\frac{R_2}{s}\right)^2+(X_1+X_2)^2\right]}$$

$$T_{FL} = \frac{3 \times 4002 \times \frac{0.3}{0.075}}{104.7\ [\left(0.2+\frac{0.3}{0.075}\right)^2+(0.5+1.1)^2}]$$

$$= \frac{480000\ x\ 4}{104.7\ [(0.2+\ 4)2+(1.6)2]} = 1920000\ /\ 104.7\ x20.2\ =\ 907.8\ N-m$$

Full load (rated) Torque = 907.8 $N-m$

Half full load torque = $\frac{\mathbf{907.8}}{\mathbf{2}} = \mathbf{453.9\ N-m}$

Before we use this value in the equation for T_d, we have to find out the other required parameters which are frequency dependent i.e., $N_s, W_s\ , X_1\ and\ X_2\ @35\ Hz\ and\ also\ V_{ph}\ 35\ Hz$

$$N_{s@35\ Hz}\ = \omega_{s@50\ Hz} \times \frac{35}{50} = 1000 \times \frac{35}{50} = 700\ RPM$$

$$\omega_{s@35\ Hz} = \omega_{s@50\ Hz}\ \times \frac{35}{50} = 104.7\ \times \frac{35}{50} = 73.29\ Rad/sec$$

$$X_{1@35\ Hz}\ = X_{1@50\ Hz} \times \frac{35}{50} = 0.5\ \times \frac{35}{50} = 0.35\ \Omega$$

$$X_{2@35\ Hz}\ = X_{2@50\ Hz}\ \times \frac{35}{50} = 1.1\ \times \frac{35}{50} = 0.77\ \Omega$$

$$V_{ph@\ 35\ Hz}\ = V_{ph}@\ 50\ Hz\ \times \frac{35}{50} = 400\ \times \frac{35}{50} = 280\ V$$

Now we can use these values in the equation for T_d and find out the slip at 35 Hz

$$T_d\ = \frac{3V_{ph}^2 \cdot \frac{R_2}{s}}{\omega_s}\ [\left(R_1 + \frac{R_2}{s}\right)^2 + (X_1 + X_2)^2]$$

Let $K\ = \frac{R_2}{s}$. Then

$$453.9\ = 3\ x\ 280^2\ \times \frac{k}{73.29}\ [(0.2 +\ K)^2\ +\ (0.35 + 0.77)^2]$$

$$453.9\ = 235200\ \frac{k}{73.29}\ [(0.04 +\ K^2 +\ 0.4K) +\ 1.2544]$$

$$= 235200 \frac{K}{73.29}\ [(1.2944 +\ K^2\ +\ 0.4K)]$$

$$453.9\ = 235200 \frac{K}{[(73.29 \times 1.2944 + 73.29\ K^2 + 29.32\ K)]}$$

From which we get:

$$43060\ +\ 33266K^2\ -\ 221892K\ = 0$$

$$K^2 - 6.67K\ +\ 1.2944\ = 0$$

$$K\ = [6.67\ \mp \frac{(6.67^2 - 5.18)^{\frac{1}{2}}]}{2} = \frac{[6.67 \mp 6.27}{2}$$

$= \frac{12.94}{2}$ or $\frac{0.4}{2}$ $i.e., 6.47$ or 0.2

But $K = \frac{R_2}{s}$ and hence $\frac{R_2}{s} = 6.47$ or 0.2 or $s = \frac{0.3}{6.47}$ or $\frac{0.3}{0.2} = 0.046$ or 1.5

But slip cannot be larger than 1 and hence slip's' at half full load torque = 0.046

Speed with 35 Hz supply frequency and half full load torque = Synchronous speed @$35Hz x\ (1 - s)$

$= 700\ x\ (1 - 0.046) = 700\ x\ 0.954 = 668\ RPM$

Speed for a frequency of 35 Hz with half full load torque = 668 RPM

Torque for a frequency of 35 Hz for a speed of 650 rpm:

This can be found out directly by using the formula for torque developed i.e.

$$T_d = \frac{3V_{ph}^2 \cdot \frac{R_2}{s}}{\omega_s} \left[\left(R_1 + \frac{R_2}{s}\right)^2 + (X_1 + X_2)^2\right]$$

and using the same parameters which we have already obtained for 35 Hz and given below again. But slip alone is required to be calculated taking $N_{s@35\ Hz}$ $= 700\ RPM\ and\ N = 650\ RPM$

$$\omega_{s@35\ Hz} = \omega_{s@50\ Hz} \times \frac{35}{50} = 104.7 \times \frac{35}{50} = 73.29\ Rad/sec$$

$$X_{1@35\ Hz} = X_{1@50\ Hz} \times \frac{35}{50} = 0.5 \times \frac{35}{50} = 0.35\ \Omega$$

$$X_{2@35\ Hz} = X_{2@50\ Hz} \times \frac{35}{50} = 1.1 \times \frac{35}{50} = 0.77\ \Omega$$

$$V_{ph@\ 35\ Hz} = V_{ph@\ 50\ Hz} \times \frac{35}{50} = 400 \times \frac{35}{50} = 280\ V$$

$$S_{@35\ Hz} = \frac{N_{s@35\ Hz} - N}{N_{s@35\ Hz}} = \frac{700-650}{700} = \frac{50}{700} = 0.071$$

Thus: $T_d = \frac{3V_{ph}^2 \cdot \frac{R_2}{s}}{\omega} \left[s\left(R + \frac{R_1}{s}\right)^2 + (X + X_1)^2\right]^2$

$$= \frac{3\ x \times 280^2\ x \frac{0.3}{0.071}}{73.29} \left[\left(0.2 + \frac{0.3}{0.071}\right)^2 + (0.35 + 0.77)^2\right]$$

$$= \frac{235200 \times 4.225}{73.29} [(0.2 + 4.225)^2 + (1.12)^2]$$

$$= \frac{993720}{73.29}(19.58 + 1.25) = \frac{993720}{(73.29 \times 20.83)} = 650.92 \text{ N} - \text{m}$$

Torque for a frequency of $35\ Hz$ for a speed of $650\ rpm\ =\ 650.92\ N - m$

Chapter-5. Control of Induction Motors and Synchronous Motors

5.1. Static Rotor resistance control:

Before explaining the static Rotor resistance control a brief introduction to the basic method of *Rotor resistance control* is given here. The speed of an Induction motor can be controlled by the introduction of an external resistance in the Rotor circuit as shown in the figure below.

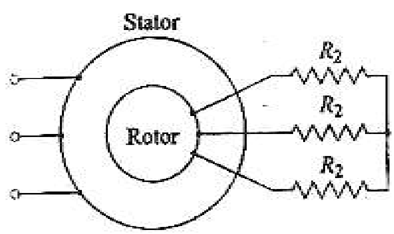


Figure 5.1. External Rotor resistances connected in a Slip Ring Induction Motor

The speed-Torque characteristics of an Induction motor with such a control are shown in the figure below.

Before studying /analyzing these characteristics, the basic Torque speed relations in an induction motor (considering *only the Rotor circuit parameters)* what we have learnt earlier are given here for a quick reference. These relations are the basis for the nature of the characteristics shown in the figure below.

• *Torque developed by the motor Td*: $T_d = k\,[s\,E_2^2\,\frac{R_2}{R_2^2} + (sX_2)^2]$

Slip at maximum torque $S_m = \frac{R_2}{X_2}$

Maximum developed Torque $T_{max} = \frac{kE_2^2}{2X_2}$

Starting torque $T_{st} = k\left[E_2^2\,\frac{R_2}{R_2^2+X_2^2}\right]$

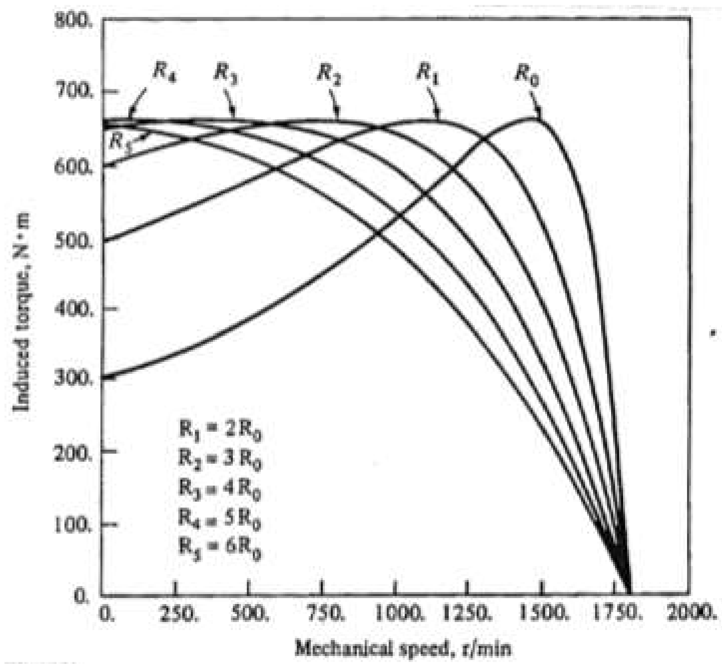


Figure 5.2. Induction Motor Torque-Speed Characteristics with variation of Rotor Resistance.

A study of the above relations along with the characteristics shows that:

- For a given Load torque, the motor speed is reduced (since slip **s** Increases) as the Rotor resistance is increased. However, the no load speed remains the same with the variation of the Rotor Resistance.
- The increase in rotor resistance does not affect the value of the maximum Torque but increases the value of Slip at which it occurs.
- With increase in Rotor resistance the starting torque increases and the

starting current reduces. Hence the *Torque to current ratio* improves.

Advantages and disadvantages of Rotor resistance control:

- External resistors can be added only during the accelerating period to increase the starting torque and can be removed later during the steady state. This minimizes the losses with dissipation in external resistors.
- The rotor temperature rise is substantially lower than it would have been if the higher resistance were incorporated in the rotor winding as in the case of squirrel cage motors. This allows the optimum utilization of the motor torque capabilities.
- It provides a constant torque operation with high Torque to current ratio.
- Though Rotor copper losses increase with decrease in speed most of it is dissipated in the external resistors. The copper losses inside the motor remains constant for a given fixed torque. Because of this, a motor of smaller size can be employed.
- Motor efficiency decreases and the rotor copper losses increase with the decrease in speed.

This is the main disadvantage and hence to overcome this, static Rotor resistance control is adopted.

5.2. Static Rotor Resistance control with a Chopper:

Instead of mechanically varying the Rotor Resistance or electrically by using contactors it can be varied electronically by using a chopper as shown in the figure below. This gives a stepless and smooth variation of Resistance and hence the Speed of the motor. In this system the external resistor is introduced in the rotor circuit after converting the slip power into DC using a three-phase bridge rectifier instead of directly connecting in the rotor circuit. Along with the resistor a chopper is also connected in parallel. By switching the chopper ON and OFF at a high frequency the effective value of the Resistance is controlled smoothly. As T_{on} is changed from 0 to its full time period of T the resistance changes from

$R\ to\ 0$. In terms of the duty ratio δ of the Chopper the effective value of the resistance R_E introduced into the Rotor is given by:

$$R_E = (1 - \delta).R$$

A filter inductor L_d is provided in series between the rectifier and the external resistor to smoothen the current I_d. A higher ripple in I_d produces higher harmonics in the rotor current and hence the rotor copper losses will increase. The diode bridge is the main contributor for the ripple and not the Chopper Switch since it operates at a relatively higher frequency.

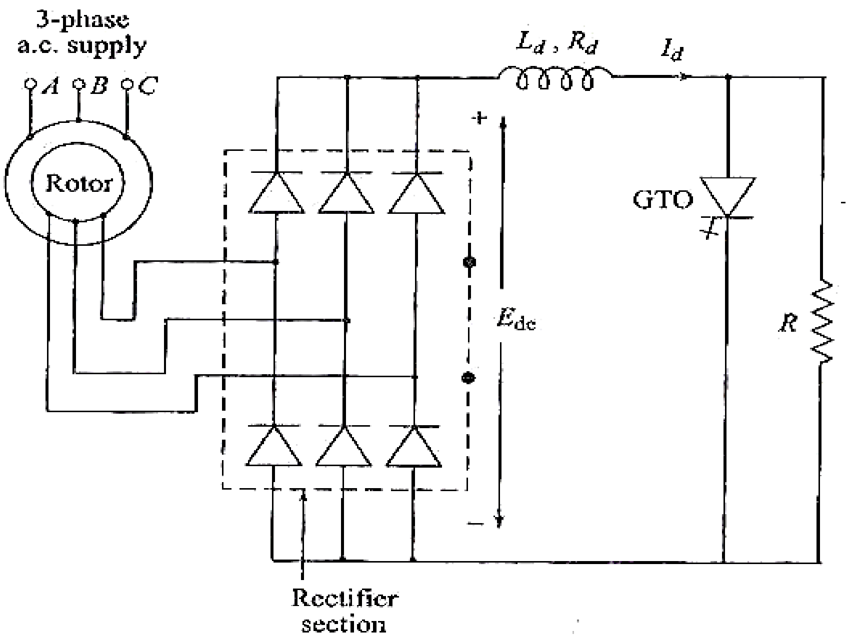


Figure 5-3. Induction Motor Speed control using a chopper

A filter inductor L_d is provided in series between the rectifier and the external resistor to smoothen the current I_d . A higher ripple in I_d produces higher harmonics in the rotor current and hence the rotor copper losses will increase. The diode bridge is the main contributor for the ripple and not the Chopper Switch since it operates at a relatively higher frequency.

The Diode Bridge Output $\mathrm{E_{DC}}$ changes from its maximum value at standstill to about 5 % at near motor rated speed. Here a Thyristor is not suitable as a Switch since reliable commutation at a higher switching frequency can be obtained only by external commutating circuits which would be bulky and expensive.

The DC voltage E_{DC} is small because Induction motors are usually designed with stator to Rotor turns ratio of greater than 1. Hence a Transistor switch is good enough for low power drives and GTO can be used for ratings beyond the capability of Transistors. Self-commutation capability of these devices ensures reliable commutation at all operating points and makes the Semiconductor switch compact.

5.3. Slip Power Recovery

We have seen that In the Rotor resistance control method, the slip power which increases with decreasing speed gets dissipated in the resistance and hence the efficiency of the system gets reduced at lower speeds. The mechanical power that can be obtained from the Air gap power is with a per unit conversion efficiency of $(1 - s)$ and the overall motor efficiency would still be lesser than this. The Air gap power is almost totally dissipated as heat in the Rotor circuits at lower speeds and hence the efficiency would be very poor. Therefore, the Rotor resistance method of speed control is very inefficient except for a very small speed range close to the synchronous speed.

However instead of dissipating the slip power in the resistance, if it can be conveniently returned to the mains or effectively utilized to increase the drive power then the Drive system becomes more efficient. This is achieved by means of two widely used *slip power recovery* methods known as *Scherbius* and *Kramer* drives. They are also called as cascade drives.

5.4. Scherbius drive

In the traditional *Scherbius* drive shown in the figure below a rotary converter rectifies the slip power and the rectified output drives a DC motor which is coupled to a squirrel cage Induction Generator. The Induction generator is driven at super synchronous speeds and returns the slip power to the same mains supply which gives supply to the Induction motor drive.

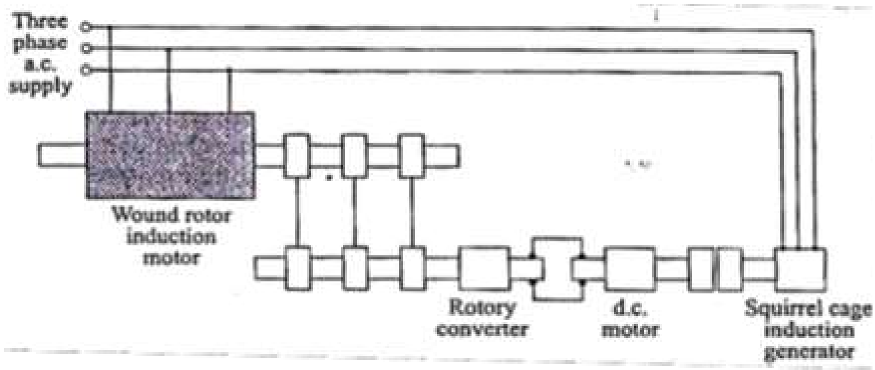


Figure 5-4. Traditional Scherbius drive.

5.4.1. Static Scherbius drive:

The static *Scherbius* drive system for the speed control of a wound rotor Induction motor is shown in the figure below. This is also known as sub synchronous converter cascade since it is capable of providing speed control only in the sub synchronous speed range.

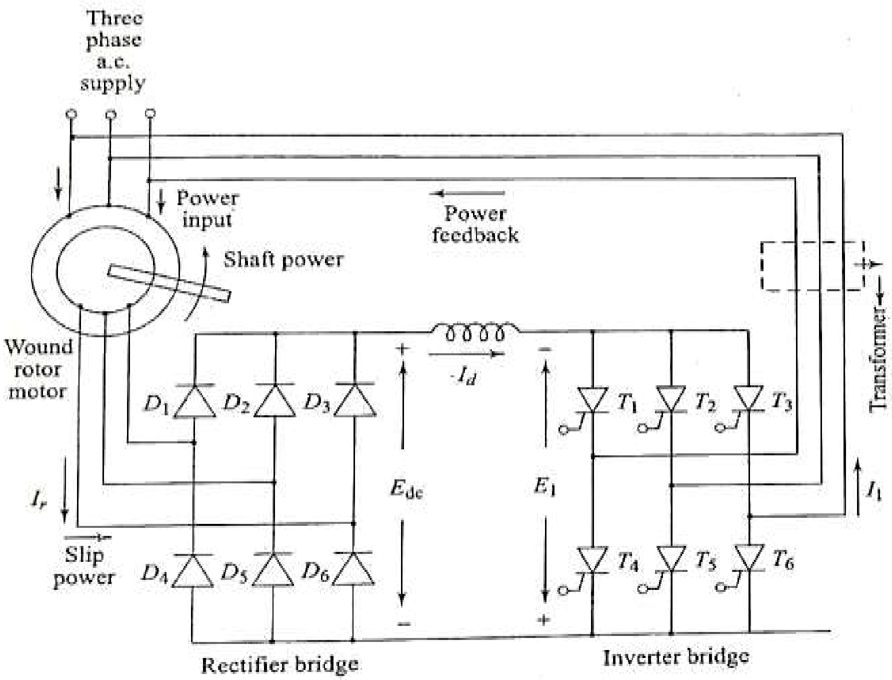


Figure 5-5. Static Scherbius drive

The DC link converter consists of a three-phase diode bridge rectifier which operates at slip frequency and feeds the rectified slip power to a phase controlled three phase Inverter through a smoothing Inductor. The inverter returns the rectified slip power to the AC supply. The rectifier and the inverter are both naturally commutated by the alternating $e.m.fs$ appearing at the slip rings of the rotor circuit and supply bus bars respectively. The problem of matching the frequencies of the injected $e.m.f$ and the rotor e.m.f is eliminated by rectifying the rotor voltage and using the variable back $e.m.f$ available from the controlled three phase inverter as the externally injected speed control voltage.

If commutation overlap is negligible the DC output voltage of the uncontrolled three phase rectifier is given by:

$E_{DC} = \frac{3E_{rm}}{\pi} = 3\frac{\sqrt{2}Er}{\pi^3} = 1.35\, E_{rs}$ where E_{rm} is the maximum value of Rotor side line voltage at stand still where E_r is the RMS value of Rotor side line

voltage at stand still
where E_{rs} is the RMS value of Rotor side line voltage in running condition with slip ‘s’

For a line commutated three phase bridge inverter with negligible commutation overlap the average back $e.m.f$ is given by:

$E_l = 1.35.E_L.cos\alpha$

Where α is the inverter firing angle ($\alpha > 90°$) and E_L is the AC line to voltage.

Neglecting the drop across the inductor,

$E_{DC} + E_l = 0 \; or \; 1.35\, E_{r.s} + 1.35.E_L.cos\alpha = 0$

And hence $s = -(\frac{E_l}{E_r}).Cos\alpha = a|cos\alpha|$

Where $a = (\frac{E_l}{E_r})$ is the effective stator to rotor turns ratio of the motor. Therefore, speed control is obtained by simple variation of the Inverter firing angle. If ‘a’ is unity the no-load speed of the motor can be controlled from near standstill to full speed as |cosα| is varied from almost unity (since the maximum value of **α** is limited about 165° for safe commutation of Inverter thyristors) to zero. This is explained in simple words as below.

- As **α** is varied from 90^0 to 167^0 |cosα|varies from 0 to almost unity (0.96)
- Assuming ‘a’ as unity we can say that slip varies from 0 to almost unity
- (0.96) as |cosα| varies from 0 to almost unity (0.96)
- So, we can say that that slip varies from 0 to almost unity (0.96) as **α** is varied from 90^0 to 167^0
- In other words, “Speed varies from *Full speed* to almost *Stand still* as **α** is varied from 90^0 to 167^0”

In practice the motor turns ratio **a** is larger than unity resulting in a lower Rotor voltage. This results in the requirement of lower value of cosα for a given lower speed and hence a lower power factor which is not desirable. To overcome this limitation a step-down transformer is introduced in between the supply lines and the Inverter as shown by the dotted lines with a turn's ratio of m. The governing relation between the firing angle (α from 90° to 165°) and the slip then becomes:

$$s = \left(\frac{a}{m}\right)|cos\alpha|$$

We know that the power factor of the converter is low at low firing angles. Hence the turns ratio 'm' of the transformer is chosen such that the drive operates always at α = 165° (|cosα|= 0.966) for the required lowest speed (highest slip S_{max}) so that the power factor is highest.

5.5. Torque-Speed relationship:

Assuming the rotor resistance to be small:

The Rotor slip power is equal to the DC link power .i.e.

$$s.P_{ag} = E_1.I_d$$

$$\boldsymbol{P_{ag} = E_1.\frac{I_d}{s}}$$

But $P_{ag} = T.\omega_s$

And hence $T = E_1.\frac{I_d}{s\omega_s}$.

Substituting the values of s = a|cosα| and $E_l = 1.35.E_L.cos\alpha$ from the earlier relations in to the above expression for torque viz. $T = E_1.\frac{I_d}{s.\omega_s}$ we finally get:

$$T = 1.35.E_L.\frac{I_d}{a.\omega_s}$$

Thus, the steady state Torque is proportional to the rectified Rotor current I_d which in turn is equal to the difference between the rectified Rotor voltage and the average back $e.m.f$ of the inverter divided by the resistance of the DC link Inductor. The inverter $e.m.f$ is constant for a fixed firing angle and hence the

Rotor slip increases linearly with load torque giving Torque- Speed characteristics similar to that of a separately excited DC motor with armature voltage control.

The complete open loop Torque-Speed characteristics of the Induction motor with a *Scherbius* drive are shown in the figure below.

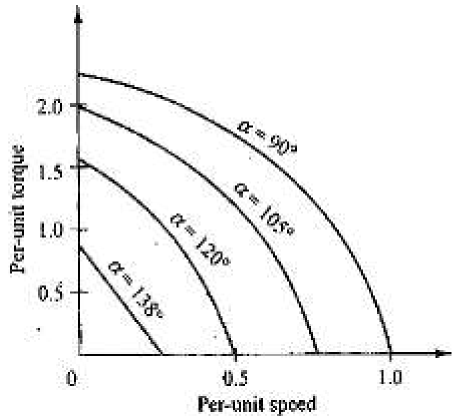


Figure 5-6. open loop Torque-Speed characteristics of an Induction motor with a Scherbius drive

5.5.1. Important features of Scherbius drive:

- Since power is fed back to the source, unlike in rotor resistance control where it is wasted in external resistors, drive has a high efficiency. The efficiency is even higher than the static voltage control for the same reason.
- Drive Input power is the difference between motor input power and the power fed back. Reactive power is the sum of the motor and inverter reactive powers. Therefore, this drive has a poor power factor throughout its range of operation.

5.6. Kramer drive:

Kramer System: The Kramer system is applicable for only sub synchronous speed operation. Figure below shows a conventional Kramer system. The system consists of a 3-phase rotary converter and a DC motor. The slip power is converted into dc power by a rotary converter and fed to the armature of the DC motor. The slip ring induction motor is coupled to the shaft of the dc motor. The slip rings are connected to the rotary converter. The dc output of rotary convener is used to drive a dc motor. The rotary converter and dc motor are excited from the dc bus bars or from an exciter. The speed of slip ring induction motor is adjusted by adjusting the speed of dc motor with the help of a field regulator. This system is also called an '*electromechanical cascade*', because the slip frequency power is returned as mechanical power to the slip ring induction motor shaft by the DC motor.

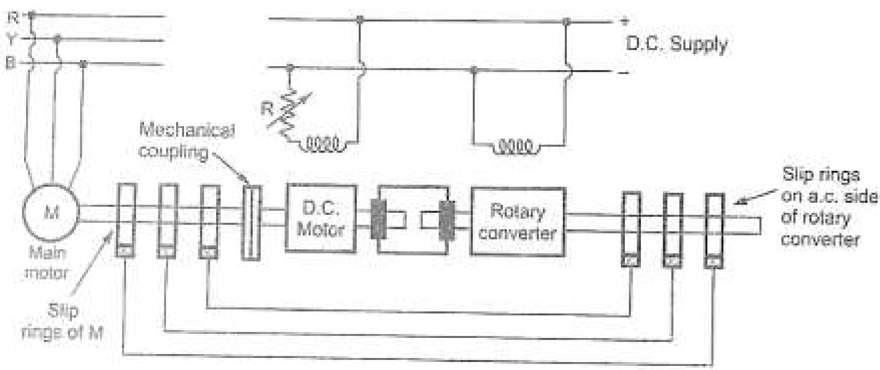


Figure 5-7. Conventional Kramer System

5.7. Static Kramer Drive:

In the Static Kramer drive the slip power is converted to DC by a Diode bridge and fed to a DC motor which is mechanically coupled to the Induction motor. Torque supplied to the motor is the sum of the torque produced by the Induction and DC motors. Speed control of the Induction motor is obtained by controlling the field current of the DC motor. A schematic diagram of this type of Static Kramer drive is shown in the figure below.

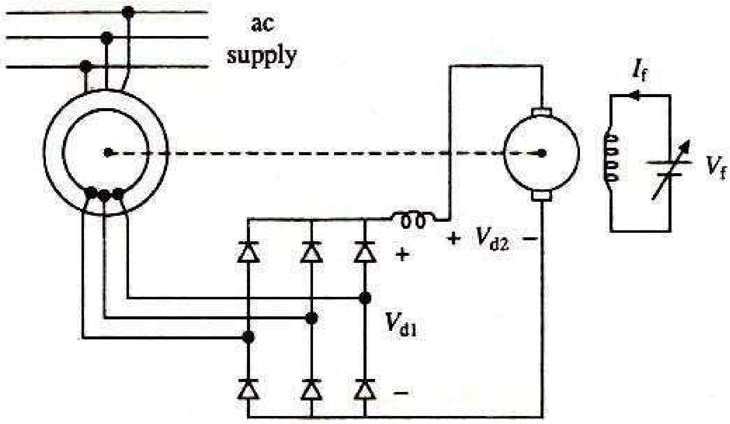
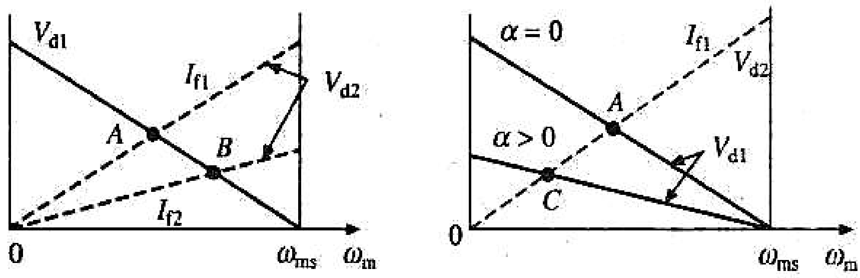


Figure 5-8. Static Kramer drive circuit

Figure (a) below shows the variations of $\mathbf{V_{d1}}$ and $\mathbf{V_{d2}}$ with speed for two values of field current. Steady state operation is obtained when $\mathbf{V_{d1}} = \mathbf{V_{d2}}$ i.e., at points **A** and **B** for field currents $\mathbf{I_{f1}}$ and $\mathbf{I_{f2}}$. With this method speed control is possible from synchronous speed to around half of synchronous speed. Below this the speed cannot be brought down. This limitation is mainly because: To increase the Speed on the lower side ***either***

- The slope of the line V_{d1} vs. Speed is to be decreased. For this, the maximum DC voltage V_{d1} is to be reduced but it is not possible from the Diode Bridge.
- *Or* the slope of the line V_{d2} vs. Speed is to be increased. i.e., the maximum value of $\mathbf{V_{d2}}$ is to be increased. This is also not possible because for a given DC motor with the maximum ratings the maximum value of speed and hence the maximum back e.m.f $\mathbf{V_{d2}}$ are fixed.

This can be clearly seen in figure (a) below.



(a) (b)

Figure 5-9. (a) Field control with Diode Bridge (b) Firing angle control of Thyristor Bridge with constant Motor field.

When larger speed range is required, the above limitation is overcome (lower limit can be brought down) by replacing the Diode Bridge with a Thyristor bridge. With this the maximum value of V_{d1} can be brought down and the slope of the line V_{d1} vs. Speed can be reduced. This increases the lower speed limit as shown in figure (b) above. As can be seen, with this change, the speed can now be controlled almost up to standstill.

Summary:

- **In Rotor resistance control:**
    - For a given Load torque, the motor speed is reduced (since slip **s** Increases) as the Rotor resistance is increased. However, the no load speed remains the same with the variation of the Rotor Resistance.
    - The increase in rotor resistance does not affect the value of the maximum Torque but increases the value of Slip at which it occurs.
    - With increase in Rotor resistance the starting torque increases and the starting current reduces. Hence the Torque to current ratio improves.
- **In a Scherbius drive**: The slip S is a function of the firing angle α of the Inverter as given by: $S = a|\cos\alpha|$**.** Where a is the effective stator to rotor

turns ratio of the induction motor and is given by a = n/m. Where **n** is the actual stator to Rotor turns ratio and m is the turns ratio of the Transformer from supply side to inverter side.

- **In a Kramer drive:**
  - The speed on the lower side is limited to about half of the synchronous speed. This is due to the fact that the maximum value of the DC output from the Diode Bridge V_{d1} cannot be brought down and maximum value of the back *e.m.f* of the DC motor V_{d2} cannot be increased.
  - This problem is eliminated by the use of a fully controlled rectifier in place of the diode bridge whose maximum value of DC output $\mathbf{V_{d1}}$ can be reduced by increasing the firing angle.

Example 5-1:

A 4 pole, 50 Hz, 3 phase induction motor has rotor has resistance of 0.2 **Ω** per phase and rotor standstill reactance of 1 **Ω** per phase. On full load it is running with a slip of 4 %. Calculate the extra resistance required in the rotor circuit per phase to reduce the speed to 1260 r.p.m., on the same load condition.

Solution:

From the given data:

$P = 4$

$f = 50Hz$

$R_2 = 0.2\,\Omega$

$X_2 = 1\,\Omega$

$s_f = 4\,\% = 0.04$

Synchronous speed is given by:

$$N_s = \frac{120f}{P} = 120 \times \frac{50}{4} = 1500\ RPM$$

Let N_1 = full load speed. Then $N_1 = N_s\,(1 - s_f)$

$= 1500\,(1 - 0.04) = 1440\,RPM$

Let N_2 = Reduced speed at the same load = $1260\,r.p.m.$

Let the new rotor resistance with extra resistance (R_{EX}) added be R'$_2$ for achieving the reduced speed N_2.

i.e., $R'_2 = R_2 + R_{ex}$ Where R_{ex} = Extra resistance

Let $T = T_1$ for $N = N_1$ and $T = T_2$ for $N = N_2$ and S_2 be the slip at reduced speed 1260 RPM.

Then $S_2 = \frac{N_S - N_2}{N_S} = \frac{1500-1260}{1500} = 0.16$

We know that:

$T \propto sE_2^2\, E_2^2 \frac{R_2}{[R_2^2+(sX_2)^2]}$

Let $T = T_1$ for $N = N_1$ and $T = T_2$ for $N = N_2$ and $R_2 = R_2$ for $N = N_1$ and $R_2 = R'_2$ for $N = N_2$

Then we get:

$$\frac{T_1}{T_2} = S_f E_2^2 \frac{R_2}{\left[R_2^2+\left(S_f X_2\right)^2\right]} \times (R'_2)^2 + \frac{(s_2X_2)^2}{s_2E_2^2\, R'_2}$$

But $T_1 = T_2$ as load is as same

Hence:

$$s_f E_2^2 R_2^*(R_2')^2 + (S_2X_2)^2 = s_2E_2^2R_2'[R_2^2 + \left(s_f X_2\right)^2]$$

Cancelling $\mathbf{E^2}$ on both sides**:**

$$\boldsymbol{sR(R^1)^2 + (s_x)^2 = sR'[R_2^2 + sX_2^2]}$$

Substituting the values from the given data we get:

i.e., $0.04 \times 0.2[(R'_2)^2+(0.16 \times 1)^2] = 0.16 \times R'_2\,[(0.2)^2 + (0.04 \times 1)^2]$

Simplifying we get: $(R'_2)^2 - 0.832\ R'_2 + 0.0256 = 0$

$$R_2' = [0.832 + \frac{\sqrt{(0.832)^2 - 4 \times 0.0256}}{2} = 0.032\Omega, 0.8\Omega$$

After adding R_{ex}, R'_2 cannot be less than R_2. So, neglecting smaller value of 0.032

we get $R_2' = 0.8 = R_2 + R_{ex}$

Hence finally: $R_{ex} = 0.8 - R_2 = 0.8 - 0.2 = 0.6\ \Omega$ per phase.

Example 5-2:

A Three phase, 440 V, 6 pole, 50 Hz, delta connected SRIM has rotor resistance of 0.3 Ω and leakage reactance of 1Ω per phase referred to stator. When driving a fan load it runs at full load at 3% slip. What resistance must be inserted in the rotor circuit to obtain a speed of 850 rpm if stator to rotor turns ratio is 2?

Solution:

Given data:

$V_{ph} = 440\ V$ (Since delta connected input line voltage = Phase

voltage) $P = 6, f = 50\ Hz, R_2 = 0.3\ \Omega, X_2 = 1\ \Omega$, full load slip

$s_f = 0.03$ Synchronous speed

$$N_s = 120 \times \frac{50}{6} = 1000\ RPM$$

and $\omega_s = 2\pi \times \frac{1000}{60} = 104.72$ Rad/sec

In this problem we can use the simple equivalent circuit with Rotor side circuit parameters alone since they are only given and stator side parameters have been neglected. Then we can use the expression we know for full load torque as

$$T = \left(\frac{3}{2\pi n_s}\right) \left[s\ E_2^2\ \frac{R_2}{R_2^2 + (sX_2)^2}\right]\ N - m$$

In this problem the values of R_2 and X_2 are given referred to stator side and hence we can work on the stator side itself except that we have to take V_{ph} in place of E_2 in the above equation and finally take the answer back to the rotor side since the Stator to Rotor side turns ratio is 2 (and not unity). Then taking the full load values we get the above equation as

$$T_{FL} = \frac{3}{\omega_s}\left[sV_{ph}^2 \frac{R_2}{R_2^2+(sX_2)^2}\right] N-m$$

Substituting the values from the given data we get:

$$T_{FL} = (\frac{3}{104.72}).[440^2.(0.03 \times 0.3) / \{(0.3)^2 + (0.03 \times 1)^2\}]$$

$$T_{FL} = 0.0286\ [193600 \times \frac{0.009}{0.0909}] = 548.21\ N-m$$

Since the load is a fan load, we know that the

$TL_a\ N^2 or\ T_L = k.N^2$ So, at the rated conditions:

$$\mathrm{T_{FL}} = 548.21 = \mathrm{k.N^2} = \mathrm{k.[N_s\ (1-s)]^2} = \mathrm{k.[1000\ (1-0.03)]^2}$$

from which we get:

$$k = \frac{548.21}{(1000\ x\ 0.97)^2} = 5.826 \times 10^{-4}\ \text{N-m/RPM}^2$$

Now let us find out the load torque at 800 RPM using the fact that $T_L = k.N^2$ and using the value of k as obtained above.

$$T_{L@800RPM} = 5.826 \times 10-4 \times 8002 = 372.86\ N-m$$

$$Slip\ @800\ RPM = \frac{1000-800}{1000} = 0.2$$

The equation (1) given above for the $T_{L@800RPM}$ then becomes:

$$T_{L@800RPM} = (\frac{3}{\omega_s}).[V_{ph}^2.\ \frac{s.k}{\{(k)^2+(sX_2)^2\}}\ ]$$

where s is now the slip $@800\ RPM$ = and k is the new rotor resistance with external resistance R_E added to the existing $R\ of\ 0.3\Omega\ i.e., k = (R_E + 0.3)$

Now substituting the corresponding torque, new rotor resistance and the slip in the above equation we get:

$$372.86 = T_{FL} = \left(\frac{3}{104.72}\right).\left[\frac{440^2.(0.2k)}{\{(k)^2 + (0.2 \times 1)^2\}}\right]$$

Then the above equation becomes:

$$372.86 = \frac{5547\times 0.2k}{(k^2 + 0.2^2)}$$ or

$372.86\, k^2 - 1109k + 372.86 \times 0.04 = 0$ or

$K^2 - 2.97\, k + 0.04 = 0$ from which we get

$$k = \frac{[2.97 \mp (2.97^2 - 4\times 0.04)^{1/2}]}{2} = \frac{(2.97 \mp 2.94)}{2} = 2.955$$ or

$0.015\ i.e. k = (R_E + 0.3) = 2.955\ or\ 0.015$ From which

R $= 2.955 - 0.3 = 2.655\ \Omega$ or $R_E = 0.015 - 0.3 = -0.015\ \Omega$

But resistance cannot be negative and hence $R_E = 2.655\ \Omega$

But this is the resistance to be added to the Rotor resistance referred to stator.

Hence value of external resistance to be added in the Rotor circuit

$$= \frac{R_E}{(turns\ ratio)^2} = \frac{2.655}{2^2} = 0.664\ \Omega$$

5.8. Introduction to control of Synchronous Motors

A synchronous motor is one in which the alternating current flows in the armature winding and DC excitation is supplied to the field winding. The armature winding is on the stator and is usually a three-phase winding. The armature is identical to that of the stator in an Induction motor but there is no Induction into the Rotor. The field winding is on the rotor which is a solid forging and the slots are milled on the surface in which the DC field windings are placed.

The balanced three phase armature currents establish a rotating magnetic field at the synchronous speed corresponding to the supply frequency ($N_s = \frac{120f}{P}$) just like in an Induction motor. If the Rotor which is supplied with a DC excitation is also made to rotate at the same synchronous speed, then the magnetic fields of stator and rotor are stationary relative to each other and a steady Torque is developed due to the tendency of the two magnetic fields to align with each other and this torque sustains the synchronous speed of the rotor. The process of initially bringing the rotor to the synchronous speed is called Starting.

Unlike an Induction motor Synchronous motor runs only at synchronous speed until the load Torque exceeds the Pull-out torque which is the Torque beyond which the motor slips out of synchronism and comes to a halt.

There are several types of synchronous motors like cylindrical Rotor motors, salient pole motors, Reluctance motors, Permanent magnet motors etc. But to understand the basic control methodology we will briefly study the equivalent circuit of a cylindrical rotor motor.

5.8.1. Equivalent circuit of a Synchronous Motor with cylindrical rotor:

A simplified per phase Equivalent circuit of a Synchronous Motor with cylindrical rotor is shown in the figure below.

X_s is the synchronous reactance and E is the excitation $e.m.f$. The power in put to the motor is given by:

$P_{in} = 3\,VI_s\,cos\varphi$

where φ is the phase angle of I_s with respect to V

Neglecting the stator loss which is small the power developed by the synchronous motor is given by:

$P_m = 3\,VI_s\,cos\varphi$

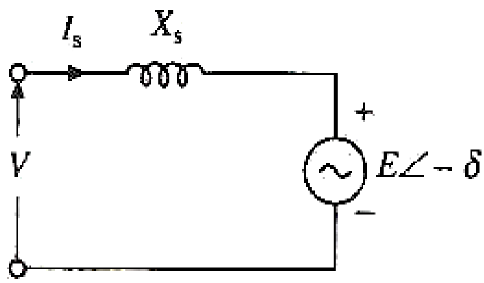


Figure 5-10. Equivalent circuit of a synchronous motor with cylindrical rotor

$$I_s = \frac{V\angle 0 - E\angle -\delta}{jX_s} = \frac{V}{X_s}\angle -\frac{\pi}{2} - \frac{E}{X_s}\angle -(\frac{\pi}{2}+\delta)$$

$$I_s cos\emptyset = \frac{V}{X_s} cos\frac{\pi}{2} - \frac{E}{X_s} cos\left(\frac{\pi}{2}+\delta\right)$$

$$I_s cos\emptyset = \frac{E}{X_s} sin\delta$$

Substituting this in the equation for P_m we get

$$P_m = \frac{3VEsin\delta}{X_s}$$

The rotating field produced by the stator moves at a synchronous speed given by:

$$\omega_{ms} = \frac{4\pi f}{P}\ rad/sec$$

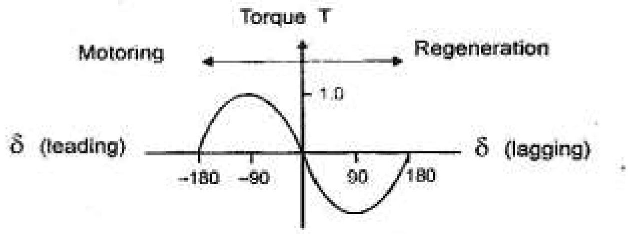
Where f is the supply frequency and P is the number of poles.

For a steady torque to be produced, rotor field must move at the same speed as the stator field. Since rotor field has the same speed as that of the Rotor the Rotor also runs at the same synchronous speed. Therefore, torque is given by:

$$T = \frac{P_m}{\omega_m} = \frac{3VE}{X_s\omega_{ms}} sin\delta$$

For a given field excitation E is constant. Therefore, P_m and T are proportional to sinδ. The angle δ is called *Torque (or Power) angle*.

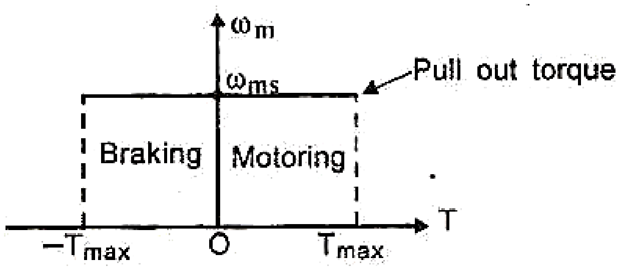
The Pull-out torque $T_{pull-out}$ (same as maximum Torque T_{max}) is reached at $\delta = \mp 90°$. If the load Torque exceeds $T_{pull-out}$ the motor pulls out of synchronism. The plot of developed torque vs. the torque angle δ is shown in the figure 5-11. (a) below.



(a) Torque versus torque angle with cylindrical rotor

Figure 5.11(a)

The Speed-Torque curve is shown in figure (b) below. Motoring operation is obtained when δ is positive i.e., E lags behind V. Regenerative braking is obtained when δ is negative or E leads V.



(b) Speed-torque characteristics with a fixed frequency supply

Figure 5-11(b).

The important feature of wound field synchronous motor is that its power factor can be controlled by varying the field current which in turn varies the excitation voltage **E.** The phasor diagrams of a synchronous motor for a given developed power are shown in the figure below. As can be seen when the field excitation is small the motor operates with a lagging power factor. The power factor can be made unity or leading by increasing the field excitation.

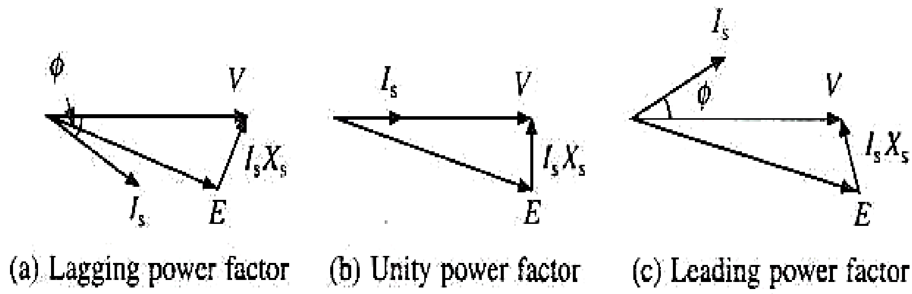


Figure 5-12. Variation of power factor with field excitation

5.9. Introduction to speed control of synchronous motors:

In synchronous motors also, in steady state, the speed is directly proportional to the supply frequency and the control methodology is same like in Induction motors. Constant flux operation below base speed is achieved by constant V/f control. Above base speed once the rated voltage is reached, the terminal voltage is kept constant and frequency is increased. The pull-out Torque T_{max} is constant during the constant flux operation where as it decreases with increase in frequency for higher speeds.

Unlike an Induction motor the synchronous motor either runs at the synchronous speed or it does not run at all. Hence the variable frequency control adopts any of the following two methods.

- True Synchronous Mode or Separate Control Mode
- Self-control Mode

5.9.1. Separate Control Mode:

This is an open loop control mode in which the stator supply frequency is controlled from an independent oscillator. Hence the frequency is gradually increased from its initial value to the final desired value so that the difference between the synchronous and rotor speed is always very small. This enables the rotor to track the changes in synchronous speed and catch up without pulling out. When the desired synchronous speed is reached, the rotor pulls into step, after hunting oscillations. This method can be used for smooth starting and regenerative braking. This method is best suited for multiple synchronous, reluctance or Permanent magnet (PM) motor drives where close speed tracking is essential among a number of machines in applications such as fiber spinning mills, paper and textile mills where accurate speed tracking is required.

The block diagram of such an open loop control system using this separate control method for multiple synchronous motors is shown in the figure below.

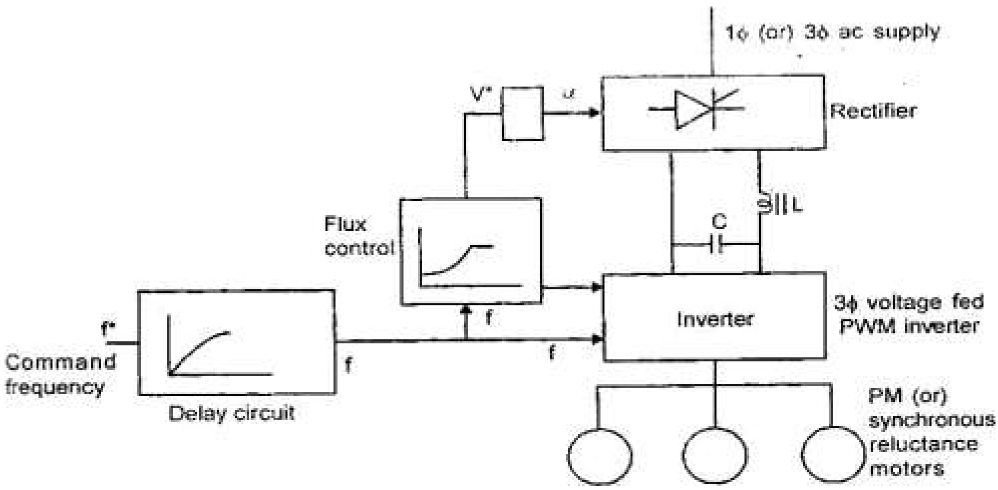


Figure 5-13. Open loop speed control of multiple PM synchronous motors.

Here all the machines are connected to the same Inverter and they move in response to the command frequency f^* at the input to the Ramp/delay circuit. The Input speed command is given through a ramp generator with a finite delay to ensure that the rotor gradually picks up speed and pulls into synchronism with the stator magnetic field and settles at the final synchronous speed. The frequency command f^* after passing through the ramp/delay circuit generates the required V and f control signals just like in a VSI with a PWM Inverter as shown in the figure. The V control is applied to the DC converter through a flux control block so as to generate the required Voltage to generate a constant flux with varying frequency. The Rectifier output then gets applied to the PWM inverter through $L\&C$ filter as required for a VSI type drive. The frequency command is directly applied to the PWM inverter. The synchronous motor can be built with damper winding to prevent oscillations.

5.9.2. Self-controlled mode:

In *Self-controlled mode*, the stator supply frequency is changed in proportion to the rotor speed, so that the rotating magnetic field produced by the stator always moves at the same speed as the rotor (Or rotor field). This ensures that the rotor runs at synchronous speed at all operating points. (In all Load conditions)

Consequently, a self-controlled synchronous motor does not pull-out out of step and does not suffer from hunting oscillations & instability associated with a step change in torque or frequency when controlled from an independent oscillator (Separate control Mode). Hence Synchronous motors working in *Self-controlled mode* of operation do not require a damper winding.

Absolute Position Sensors are mounted on the Rotor shaft to track the rotor position and speed. These sensors are called rotor position sensors. The frequency and Phase of the Inverter output power are controlled by taking feedback from the Absolute position sensor. Hence, the stator supply frequency can be made to track the frequency of these signals.

Alternatively, since the voltage induced in the stator phase has a frequency proportional to rotor speed, self-control can also be realized by making the stator supply frequency track the frequency of induced voltages.

The basic block diagram of a self-controlled synchronous motor fed from a three-phase inverter and working with Rotor Position sensors is shown in the figure below.

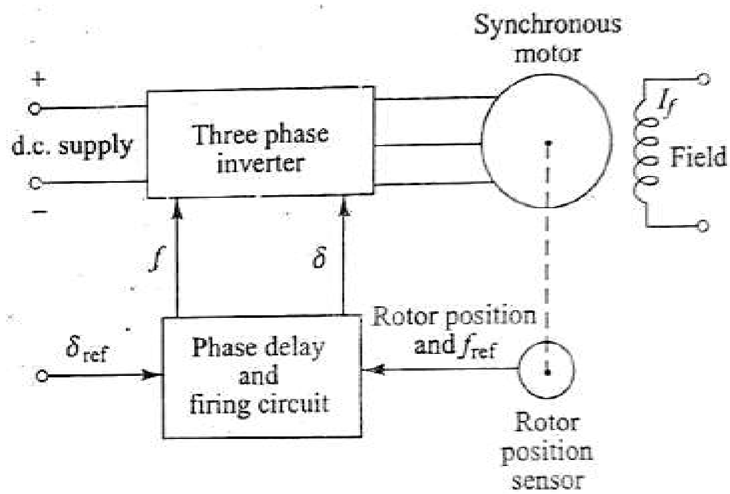


Figure 5-14. Self-Controlled Synchronous Motor (Brush Less DC Motor)

When an inverter is used the input is a DC source. The stator winding of the machine is fed from the inverter which generates a variable voltage variable frequency sinusoidal supply.

Here the frequency and phase angle **δ** of the control signal required to generate the required input to the synchronous motor is produced by comparing the Position output and frequency (f_{ref}) of the absolute position sensor, thus giving it the self-control characteristic. Here the phase angle of the pulse train from the position sensor can be delayed by an external δ_{ref} command as shown in the figure.

Operation of the drive is similar to that of a DC motor. The rotor position sensor and inverter now perform the same function as brushes and commutator in a DC motor.

Due to similarity in operation of a DC motor, an inverter fed Synchronous motor drive as shown in this figure is also known as a *Commutator Less DC Motor* ($CLDM$). If the synchronous motor is a permanent magnet motor or a reluctance motor or wound field motor with a brushless excitation, then it is a known as a Brush Less and Commutator Less DC Motor or simply a *Brush Less DC Motor* ($BLDC$). This type of Self-controlled systems driving synchronous motors offer the linear Torque speed characteristics of DC motors and are finding increasing applications in servo drives.

In this kind of control the machine behavior is decided by the torque angle and voltage/current. Such a motor can be considered as a DC motor with its commutator replaced by a fully controlled converter connected to the stator. Such a self-controlled motor has the properties of a DC motor both under steady state and dynamic conditions. Hence it is called a Commutator Less Motor (CLM). These motors have better stability performance.

Alternately the firing pulses for the inverter can be obtained from the phase angle of the stator voltages in which case the rotor position sensor can be dispensed with. When synchronous motors are over excited (field current is large) they will work with a leading power factor and can supply the reactive power required for commutation of thyristors. In such a case the induced voltages in the synchronous motor provide the required voltages for commutation of the thyristors in the inverter just as in a line commutated Inverter.

Here the firing angles are synchronized with the motor induced voltages and hence they serve both for control as well as commutation. Hence the frequency of the inverter will be same as that of the motor induced voltages. This type of inverters is called load commutated Inverters (LCI). Hence the commutation is simple due to the absence of diodes, capacitors and auxiliary thyristors.

But this natural commutation is not possible at low speeds up to 10% of base speed as the motor voltages are not sufficient to provide satisfactory commutation. At that time forced commutation must be employed.

5.10. Load commutated CSI fed synchronous motor:

The circuit diagram of a self-controlled synchronous motor drive employing a load commutated thyristor Inverter is shown in the figure below. This drive consists of two parts: Source side converter and load side converter.

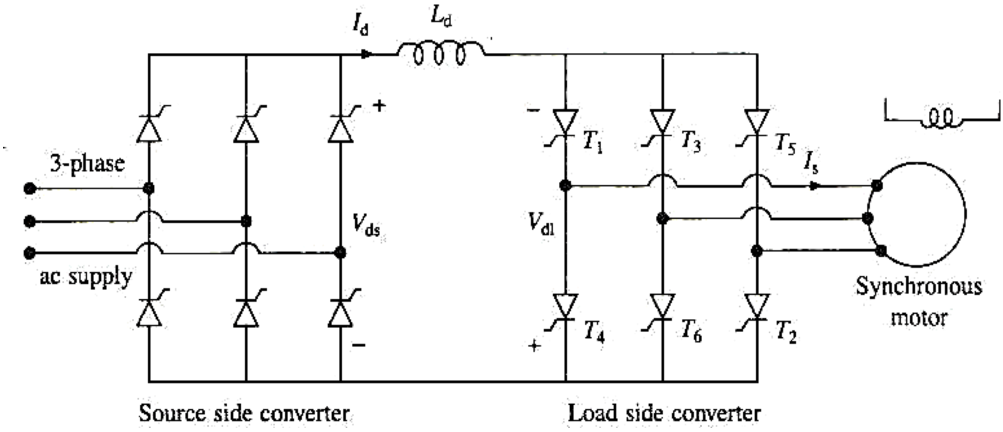


Figure5-16. Self-controlled Synchronous Motor Drive employing Load Commutated Inverter

The source side converter is a 3 phase 6 pulse line commutated fully controlled converter. When the firing angle range is $0° < \alpha s < 90°$ the converter acts as a line commutated fully controlled rectifier. During this mode the output voltage V_{ds} and output current I_{ds} are both positive.

When the firing angle range is $90° < \alpha s < 180°$ the converter acts as a line commutated fully controlled inverter. During this mode the output voltage V_{ds} is negative and output current I_{ds} is positive.

When the synchronous motor operates at a leading power factor, thyristors of the load side converter are commutated by the motor induced voltages just as the thyristors in a line commutated converter are commutated by the supply voltages. This is called Load commutation (here load is synchronous motor). Firing(triggering) angles are referred to the induced voltages just like the triggering angles in a line commutated inverter are referred to the supply voltages.

When the firing angle range is $0° < \alpha l < 90°$ the load side converter acts as a line commutated fully controlled rectifier. During this mode the output voltage V_{dl} and output current I_d are both positive.

When the firing angle range is $90° < \alpha l < 180°$ the *load side* converter acts as a line commutated fully controlled inverter. During this mode the output voltage V_{dl} is negative and current I_d is positive.

For $0° < \alpha s < 90°$ & $90° < \alpha l < 180°$ and with $V_{ds} > V_{dl}$ the source side converter acts like a line commutated Rectifier and load side Converter acts like a line commutated Converter causing power to flow from the source to the motor thus giving motoring operation.

When the firing angles are changed such that $90° < \alpha s < 180° \; and \; 0° < \alpha l < 90°$ the Load Side Converter acts like a line commutated Rectifier and Source Side Converter acts like a line commutated Inverter causing power to flow from the motor to the source thus giving regenerative braking operation.

The magnitude of Torque depends on $(V_{ds} - V_{dl})$. The motor speed can be controlled by control of line side converter firing angles.

When working as an Inverter, the firing angle has to be less than 180° to take care of commutation overlap and turn off of thyristors. It is common to define a commutation lead angle for load side converter as

$$B_l = 180° - - \alpha_l$$

If commutation overlap is ignored, the input AC current of the converter will lag behind the input AC voltage by an angle α_l. Since motor input current has an opposite phase to converter input current, the motor current will lead its terminal voltage by an angle β_l. Therefore, the motor operates at a leading power factor. Lower the value of β_l, higher the motor power factor and lower the Inverter rating.

In a simple control scheme, the drive is operated at a fixed value of commutation lead angle β_{lc} for the load side converter working as an Inverter and at $\beta l = 180° (or \; \alpha l = 0°)$ when working as a rectifier. When good power factor is required to minimize converter rating, the load side converter when working as an inverter is operated with constant margin angle control.

5.11. Closed loop operation of Synchronous drives:

A closed loop speed control scheme of a Load Commutated Inverter (LCI) Synchronous Drive is shown in the figure below.

- It employs outer speed control loop and inner current control loop with a limiter just as in a DC motor speed control system.
- The phase-controlled Thyristor rectifier on the supply side of the DC link has a constant current regulating loop and operates as a controlled current source.
- The regulated DC current is delivered through the DC link inductor to the Thyristors in the LCI (Load Commutated Inverter) (shown in the figure as Load side Inverter) which supplies square-wave line currents to the synchronous motor.
- The terminal voltage sensors generate reference pulses of same frequency as the motor-induced voltages. The phase delay circuit shifts the reference pulses suitably to obtain control at a constant commutation lead angle β_{lc}.
- Depending on the sign of speed error, β_{lc} is set to provide motoring or braking operation. Speed ω_m can be sensed either from the terminal voltage sensor or from a separate tachometer.

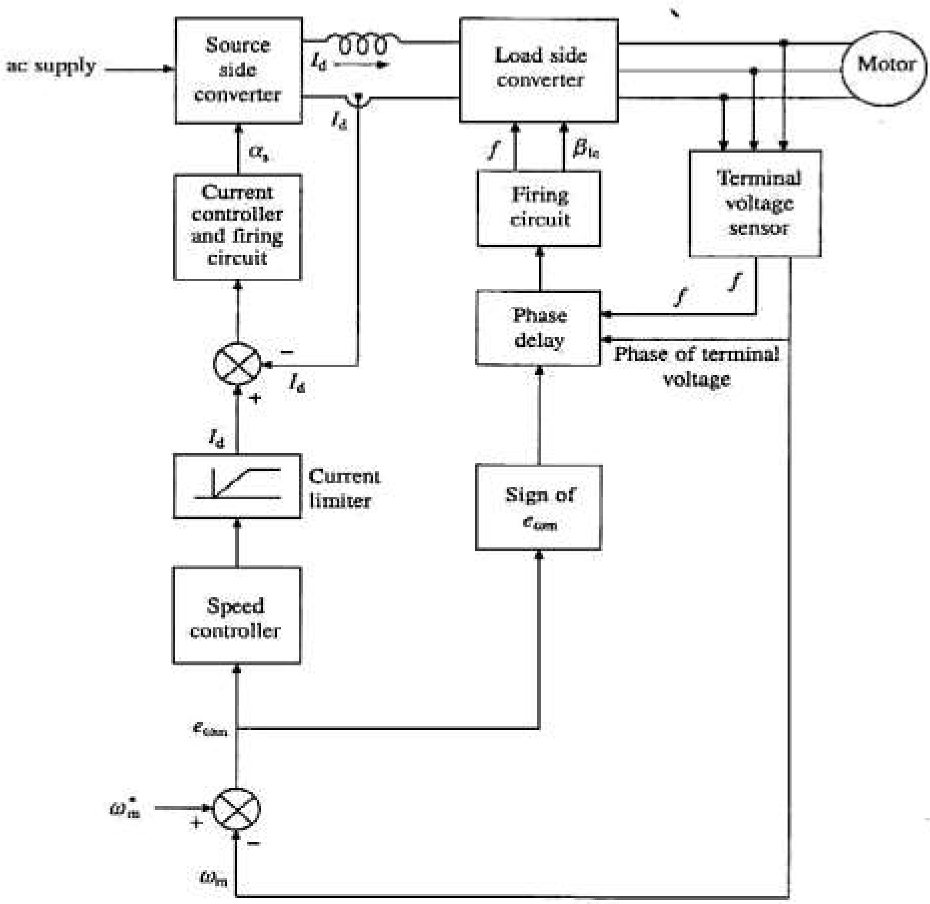


Figure 5-17. closed loop speed control scheme of a Load Commutated Inverter (LCI) Synchronous Drive

An increase in reference speed ω_m produces a positive speed error. B_{lc} value is then set for motoring operation. The speed controller and the current limiter set the DC link current reference at the maximum permissible value. The motor accelerates fast. When close to the desired speed the current limiter desaturates and the drive settles at the desired speed and at a DC link current which balances motor and load torques.

Similarly, a reduction in reference speed produces a negative speed error. This sets β_{lc} for regenerative braking operation (i.e., 180 °) and the motor decelerates.

When speed error changes sign β_{lc} value is set for motoring operation and the drive settles at the desired speed.

Advantages:

- High efficiency, four quadrant operations with regenerative braking, high power ratings (up to 100Mw) and ability to run at high speeds (6000 RPM) are some important advantages of this drive.

Applications:

- Wound field Synchronous motors are used in large power drives.
- Permanent motor synchronous motors are used in medium power drives.
- Some prominent applications are high speed and high-power drives for compressors, blowers, fans, pumps, conveyors, steel rolling mills, main line traction, ship propulsion and aircraft test facilities.

5.12. Cycloconverter fed Synchronous Motor:

In a synchronous motor fed from a VSI or a CSI, the DC link converter has two stage conversion devices that produce variable voltage and variable frequency. But with a Cycloconverter both variable voltage and variable frequency can be obtained using a single stage conversion. A Cycloconverter gives high quality sinusoidal output voltage and hence the resulting current is also sinusoidal. Consequently, the effects of harmonic current such as heating losses and torque pulsations are minimal compared to VSI or CSI fed drives. The power circuit diagram of a Cycloconverter feeding a synchronous motor and total drive system operating in a Self-Control mode/Commutator less Motor (CLM) Mode is shown in the figures (a) and (b) below.

The Cycloconverter can be Line commutated or load commutated. In Line commutated mode it provides a variable frequency, variable voltage source. It works in self-controlled mode and receives its firing pulses from rotor position sensors or armature voltage sensor. Due to its limitations in the output frequency, a line commutated Cycloconverter speed control range is limited to zero to about one third of the base speed. In Load commutated mode the motor operates on trapezoidal excitation as a current source fed motor. In this mode the motor can run up to and even beyond its base speed. The other features of four quadrant mode of operation and good power factor remain same as in a Line commutated Cycloconverter.

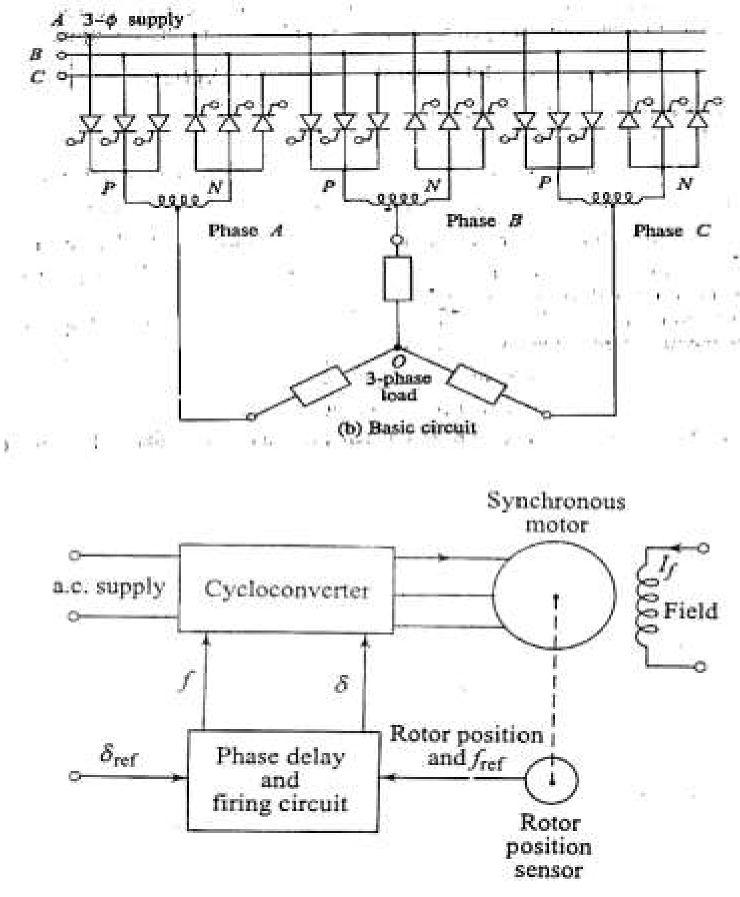


Figure 5-18. Cycloconverter feeding a 3 Phase Synchronous Motor in Self Control Mode /Commutator less Motor (CLM) Mode Voltage Source Converter (VSI) fed Synchronous Motor

The basic principle of operation of VSI drives for Synchronous Motors is same as that of $VSIs$ we have studied for Induction Motor Drives. Just like in Induction

Motor drives three basic configurations are possible to provide variable voltage/variable frequency supply to synchronous motors fed from

- Square wave inverters
- PWM inverters
- Chopper with square wave inverters

In all these cases the Synchronous motors can be operated in either self-control or separate control modes. The above three schemes in these two modes are depicted in the figures (a) to (e) below and explained briefly.

5.12.1. Separate control of a Synchronous Motor with a square wave inverter:

The Phase Controlled rectifier varies the DC voltage to the inverter and at the same time the inverter output frequency is varied based on a speed control signal from a crystal oscillator. The section between the DC source and the Inverter is known as the DC link and it includes a series Inductance and large capacitance which smoothes the DC voltage to an almost constant value. The above system cannot regenerate since current flow cannot be reversed in a phase-controlled converter. If regeneration is required it can be obtained by replacing the phase-controlled rectifier with a Dual Converter.

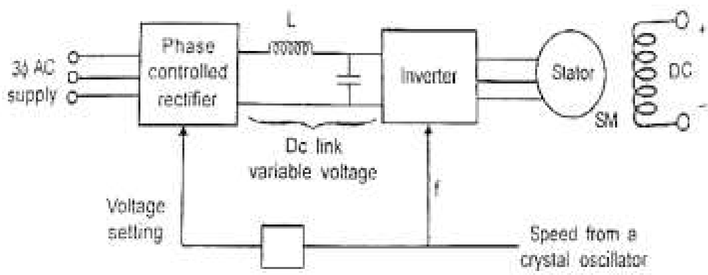


Figure 5-19. Separate control of a Synchronous motor with a PWM inverter

5.12.2. Separate control of a Synchronous Motor with a PWM inverter:

A system in which the DC link voltage is constant as obtained from a simple Diode rectifier is shown in figure (b). In this scheme the Inverter is a PWM based system and it varies both the voltage and the frequency as controlled from an external oscillator.

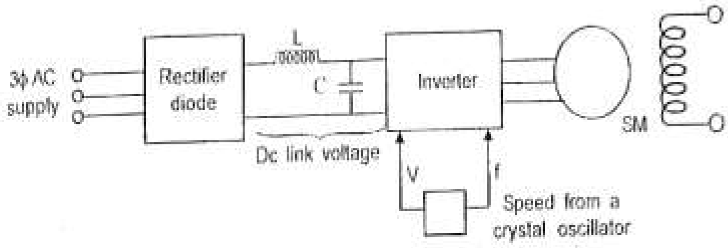


Figure 5-20. Separate control of SM fed from PWM inverter

5.12.3. Self-control of a Synchronous Motor with a square wave inverter:

The Phase Controlled rectifier output DC voltage to the inverter is varied with a speed control loop as shown in the figure and at the same time the inverter output frequency is varied both based on a control signal from a rotor sensor or armature induced voltage so as to maintain a constant $\frac{v}{f}$ ratio. The section between the DC source and the Inverter is the DC link as already explained.

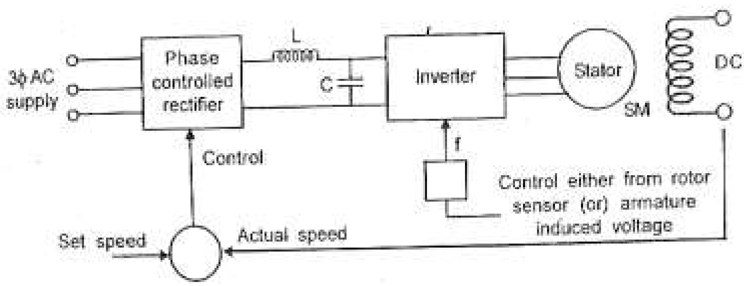


Figure 5-21. Self-control of SM fed from square wave inverter

5.12.4. Self-control of a Synchronous Motor with a PWM inverter:

A system in which the DC link voltage is constant as obtained from a simple Diode rectifier is shown in figure (d). In this scheme the Inverter is a PWM based system and it varies the voltage with a speed control loop as shown in the figure and at the same time the inverter output frequency is varied both based on a control signal from a rotor sensor or armature induced voltage so as to maintain a constant $\frac{v}{f}$ ratio.

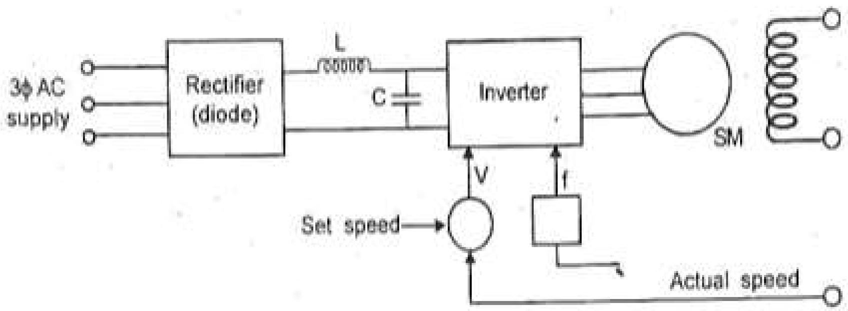


Figure 5-22. self-control of synchronous motor fed from a PWM inverter

In the fifth scheme the variation of voltage is obtained by a chopper. Due to the chopper the harmonic injection into the AC supply is reduced. This scheme is a combination that is used when a high frequency output is required and hence a PWM inverter is not used and a normal square wave inverter is used.

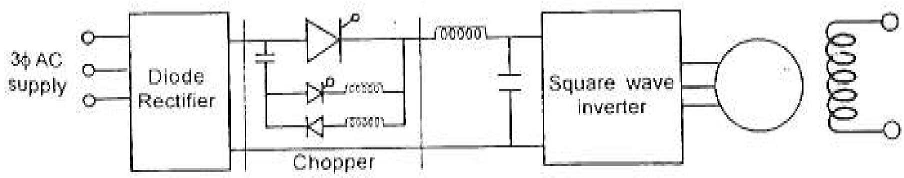


Figure 5-23. Possible combinations of VSI fed Synchronous Motor.

Chapter-6.

Special Electrical Drives and Control

6.1. BLDC drive control

A BLDC driver is an electronic device that controls the operation of a BLDC motor by managing its power, speed, and direction. Unlike brushed DC motors, which rely on brushes and commutators, BLDC motors require electronic commutation making the driver an essential component for proper functioning.

The BLDC driver regulates the motor's performance by switching the direction of current in stator windings in synchronization with the rotor position. It is achieved using control algorithms such as trapezoidal, sinusoidal, or field-oriented control (FOC), ensuring smooth and efficient operation.

The BLDC drivers operate using either sensor-based or sensor less techniques to determine the rotor's position. Hall effect sensors or encoders provide feedback in a sensor-based system, while sensor less drivers detect position using back-EMF which reduces cost and complexity.

BLDC drivers are widely used in applications requiring high efficiency, precise speed control, and minimal maintenance, such as industrial automation, robotics, electric vehicles, drones, and household appliances.

6.1.1. Components of BLDC Driver

A BLDC driver consists of several key components that work together to control the motor's operation efficiently. Key components include:

- **Microcontroller (MCU) / Digital Signal Processor (DSP):** It acts as the brain of the driver and executes control algorithms such as trapezoidal, sinusoidal, or field-oriented control (FOC). It processes sensor feedback or back-EMF signals to determine the rotor position and adjust the commutation accordingly.
- **Gate Driver Circuit:** It amplifies the control signals received from microcontrollers to drive the power switches such as MOSFETs or IGBTs. It also ensures proper switching timing and voltage levels for efficient operation.
- **Power Stage (MOSFETs / IGBTs):** It handles the high-power switching to control current flow through the BLDC motor windings. They typically consist of a three-phase inverter bridge to energize the motor coils in the correct sequence.

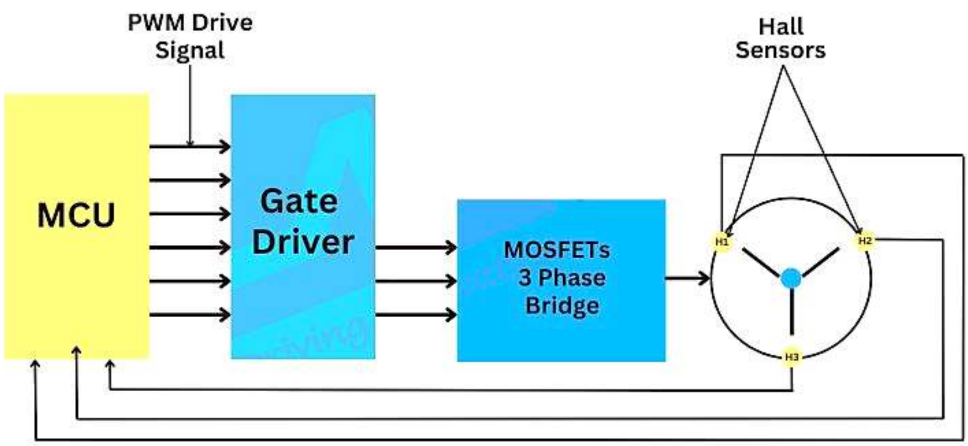


Figure 6-3. Components of BLDC driver

- **Current and Voltage Sensors:** They monitor the BLDC motor's parameters to ensure proper operation and protection against overcurrent or Under-voltage conditions. They are used in closed-loop control systems for precise speed and torque regulation.

- **Position Sensors:** They detect the rotor position for accurate commutation in a sensor-based system. In sensor less drivers, back-EMF detection or other algorithms are used to estimate the rotor position.

6.1.2. Working Principle of BLDC Driver

The **BLDC driver** controls the operation of the brushless DC motor by electronically commutating the stator windings in synchronization with the rotor position. Since BLDC motors lack brushes and commutators, the BLDC driver plays a crucial role in switching the current flow to achieve continuous rotation.

The first step in working the BLDC driver is rotor position detection. The BLDC driver detects the rotor position using hall effect sensors or other sensor less control techniques such as back-EMF detection. This information helps to decide which stator coil needs to energies next to ensure proper commutation.

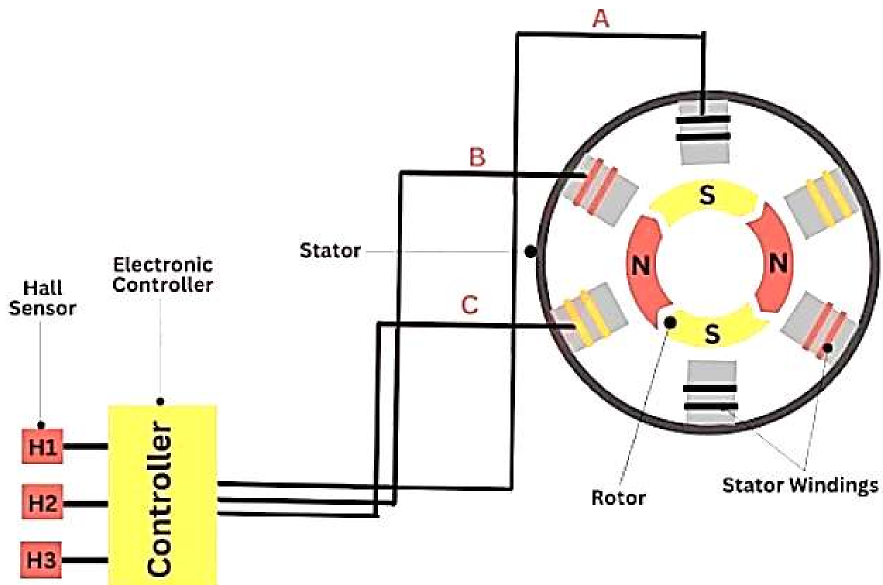


Figure 6-4. Working principle of BLDC driver

Next, the BLDC driver performs electronic commutation. Based on the rotor's position, it activates specific MOSFETs or IGBTs in a three-phase inverter bridge. This process generates a rotating magnetic field in the stator.

In trapezoidal control, current switching follows a six-step sequence while in sinusoidal and field-oriented control (FOC), current is applied smoothly for improved efficiency and torque performance.

For speed and torque control, the BLDC driver adjusts the PWM (Pulse Width Modulation) duty cycle to regulate the speed of the LDC motor. It also uses current feedback to ensure optimal torque delivery based on load conditions.

Lastly, the BLDC driver incorporates protection and efficiency optimization features. It includes overcurrent, overvoltage, and thermal protection to prevent damage. Advanced BLDC drivers further optimize energy efficiency by dynamically adjusting power delivery.

6.1.3. Factors to Consider When Choosing a BLDC Driver

When selecting a BLDC driver, several factors must be considered to ensure compatibility, efficiency, and optimal performance. Some of the key factors are:

- **Voltage and Current Ratings**: The *BLDC driver* must match the operating voltage and current requirements of the BLDC motor. Overrated or underrated drivers can lead to inefficiencies or damage.
- **Control Method**: Trapezoidal control offers simpler implementation but may cause torque ripple. Sinusoidal and Field-Oriented Control (FOC) provide smoother operation and better efficiency.
- **Sensor-Based vs. Sensor less Operation**: Hall sensor-based drivers provide precise control but add cost and complexity. Sensorless drivers rely on back-EMF detection which reduces wiring but requires sophisticated algorithms.
- **Application-Specific Requirements**: Compact size, thermal management, and programmability play a role in selecting the right driver for applications like drones, robotics, or industrial automation.

6.1.4. Types of BLDC Motor Drivers

BLDC (Brushless DC) motor drivers come in various types and sizes. Each type of BLDC driver is tailored to specific applications and performance requirements.

Here are some common types of BLDC drivers:

6.1.4.1. Sensor-based BLDC Driver

Sensor-based BLDC drivers are essential for applications that require precise control over the speed and position of the motor. These drivers use feedback from sensors such as Hall effect sensors or encoders to accurately determine the rotor position. This information enables drivers to perform the proper commutation of the motor phase and ensure optimal interaction between the stator and rotor. Therefore, these drivers offer superior performance in terms of speed regulation, torque reduction, and position accuracy. They are well-suited for applications such as robotics, industrial automation, and medical devices, where precise control and reliability are required.

6.1.4.2. Sensor less BLDC Driver

Sensor less BLDC drivers enable precise control over the speed and position of the motor without the need for external position sensors such as Hall effect sensors.

These drivers use techniques such as back electromotive force (EMF) sensing or other algorithms to estimate the rotor's position. By analyzing the EMF signals based on the motor and system, sensor less drivers accurately determine the position of the rotor and adjust the commutation accurately. This approach eliminates the cost and complexity of the sensor-based driver and makes these drivers cost-effective.

These drivers are suitable for applications where cost and size are constraints such as consumer electronics, automotive systems, and industrial automation.

6.1.4.3. Sinusoidal BLDC Driver

Sinusoidal BLDC drivers produce sinusoidal current in motor windings and offer an advantage in applications where low noise and vibration are required. Unlike other drivers, which generate torque in steps, sinusoidal BLDC drivers provide smooth torque delivery throughout the motor rotation and result in less torque ripple and smooth operation. By providing smoother torque it reduces mechanical stress on components and ensures precise motion control.

These make Sinusoidal BLDC drivers suitable for applications such as electric vehicles, drones, and medical equipment where a balance of smooth operation, and reduced noise and vibration is required.

6.1.4.4. Trapezoidal BLDC drivers

Trapezoidal BLDC drivers are known for their simplicity, reliability, and cost-effectiveness in various applications. Trapezoidal BLDC drivers offer trapezoidal current in motors winding through a straightforward commutation method. Their straightforward design makes them robust and offers reliable performance even in challenging conditions. Additionally, their ease of installation and compatibility with the motor control system offer a perfect balance of performance, reliability, and affordability.

This makes trapezoidal BLDC drivers a popular choice for a wide range of industrial and consumer applications such as where consistent and reliable motor operation is a concern.

6.1.4.5. Integrated BLDC drivers

Integrated BLDC drivers consolidate all the critical components into a single, compact package. It integrates driver circuitry, power MOSFETs, current sensing capabilities, and protection features and offers a comprehensive solution. Additionally, integrating all components into a single board reduces the material cost and simplifies the assembly process. Furthermore, the reduction in external components enhances the system's reliability contributes to the longevity and performance of the motor control system, and makes them the preferred choice for applications where space is constrained.

6.1.5. Applications of BLDC Motor Drivers

BLDC (Brushless DC) drivers find applications across various industries and sectors where precise control over motor speed, torque, and position is essential.

Some common applications of BLDC drivers include:

- **Industrial Automation**: BLDC drivers are extensively used in industrial automation for controlling conveyor systems, robotic arms, CNC machines, and packaging equipment. Their precise speed and position control ability ensure efficient and smooth operation in the manufacturing and assembly process.
- **Electric Vehicles**: **BLDC drivers** play a crucial role in electric vehicles, where these drivers control the motor system that drives the electric vehicle system. These drivers offer efficient and reliable motor control, improved performance, and energy efficiency to electric vehicles.
- **HVAC System**: HVAC systems use BLDC drivers in fans and blowers to regulate the airflow and maintain the optimal temperature in buildings and commercial spaces. These drivers offer energy efficiency operation and precise speed control, resulting in reduced energy consumption and quieter operation.
- **Consumer Electronics**: BLDC drivers are found in a wide range of consumer electronics such as computer cooling fans, hard disk drives, electric shavers, and kitchen appliances like blenders and mixers. Their compact size, energy-efficient features, and precise control make them ideal for applications that require continuous motor operation in compact size.
- **Medical Devices**: BLDC drivers are used in a wide range of medical devices such as infusion pumps, ventilators, centrifuges, and surgical tools. They provide precise control over the speed and position of the motor and ensure safe and reliable operation in critical healthcare applications.

6.2. Switched Reluctance Motor (SRM) drive control

Switched Reluctance Motor (SRM) drive control is a crucial aspect of operating Switched Reluctance Motors, which are gaining increasing attention in various applications due to their unique characteristics.

6.2.1. What is an SRM?

A Switched Reluctance Motor is a type of electric motor that operates on the principle of reluctance torque. Unlike conventional motors, it has no permanent magnets or windings on the rotor. Both the stator (stationary part) and rotor (rotating part) have salient poles (protruding poles). The stator has concentrated windings on its poles.

The fundamental principle is that the rotor always tries to align itself with the path of least magnetic reluctance. When a stator winding is energized, it creates a magnetic field that pulls the nearest rotor pole into alignment, thereby producing torque.

6.2.2. How SRM Drive Control Works:

The control of an SRM is critical because its torque production is highly dependent on the precise timing and magnitude of the current pulses supplied to the stator windings. Here's a simplified overview:

- **Rotor Position Sensing:** To achieve continuous rotation and controlled torque, the exact rotor position must be known at all times. This is typically done using a rotor position sensor (e.g., an encoder or resolver). Some advanced control schemes also explore "sensor less" operation, where rotor position is estimated from motor electrical parameters.
- **Electronic Commutation:** Unlike brushed DC motors that use a mechanical commutator, SRMs use power electronics (typically an asymmetric half-bridge converter) to switch the current to the stator windings.
- **Sequencing and Timing:** The control system sequentially energizes the stator phases in a precise order, ensuring that the magnetic field "leads" the rotor poles, pulling them forward and creating continuous rotational motion. The timing of when each phase is switched "on" (turn-on angle) and "off" (turn-off angle) is crucial for efficient operation and torque control.
- **Current/Torque Control:**
    - **Current Chopping Control (CCC):** At low speeds, the phase current can be controlled by chopping (rapidly switching on and off)

the voltage to maintain a desired current level, thereby controlling the output torque. This is a constant torque control mode.
  - **Angular Position Control (APC):** At high speeds, the back-EMF becomes significant. In this mode, the on-off switching of the phase is controlled based on the rotor position, allowing for constant power operation. Lead angle control (advancing the turn-on angle) is often used at higher speeds to optimize performance.
- **Advanced Control Strategies:** Due to the inherent non-linearity of SRMs and challenges like torque ripple and acoustic noise, advanced control techniques are employed, including:
  - **Direct Torque Control (DTC):** Directly controls the instantaneous output torque.
  - **Direct Instantaneous Torque Control (DITC):** A variation of DTC.
  - **Torque Sharing Function (TSF)-based control:** Distributes torque among active phases to minimize ripple.
  - **Model Predictive Control (MPC):** Predicts future motor behavior and optimizes control actions.
  - **AI-based approaches (e.g., fuzzy logic, neural networks, sliding mode control):** Used to address non-linearity and improve performance.
  - **Optimization of switching angles:** Determining optimal turn-on and turn-off angles to minimize torque ripple and copper losses.

6.2.3. Advantages of SRM Drive Control:

- **Simple and Robust Motor Structure:** No windings, magnets, or commutator on the rotor, leading to high reliability and suitability for harsh environments.
- **High Fault Tolerance:** Phases are electrically isolated, so the motor can continue operating with reduced capacity even if one or more phases fail.
- **Wide Speed Range:** Can operate efficiently from very low to very high speeds.
- **High Efficiency over Wide Range:** Can maintain high efficiency across a broad range of speeds and loads.

- **Good Starting Torque and Low Starting Current:** Suitable for heavy-load starting.
- **Flexible Control:** Allows for easy four-quadrant operation (motoring and generating in both directions) and regenerative braking.
- **Cost-Effective:** Absence of permanent magnets reduces manufacturing cost.
- **No Shoot-Through Fault:** The power converter topology inherently avoids direct short circuits across the DC supply.

6.2.4. Disadvantages of SRM Drive Control:

- **High Torque Ripple:** Due to its doubly salient structure and pulsed excitation, SRMs inherently produce significant torque ripple, which can lead to vibration and noise. This is a major challenge for applications requiring smooth operation.
- **Acoustic Noise:** Related to torque ripple and radial forces, SRMs can be noisy.
- **Complex Control System:** Requires precise rotor position sensing and sophisticated control algorithms to mitigate torque ripple and achieve smooth operation, making the control more complex than some other motor types.
- **Requires Position Sensor:** Historically, a rotor position sensor was essential, adding to the system's complexity and cost (though sensor less control is an active research area).

6.2.5. Applications of SRM Drive Control:

Despite the challenges, the advantages of SRMs make them suitable for a growing number of applications:

- **Electric Vehicles (EVs):** Attractive due to their robustness, magnet-free design, fault tolerance, and efficiency, especially in scenarios with frequent starts/stops and wide speed ranges. Research focuses on reducing torque ripple for smoother EV operation.
- **Industrial Applications:**

- **Textile machinery:** Low starting current, high torque, fast dynamic response, and variable speed capabilities.
- **Pumping units:** High efficiency at varying loads, frequent direction changing.
- **Heavy-load starting applications:** Forging equipment, planers.

- **Household Appliances:** Washing machines, vacuum cleaners, fans, cooking machines.
- **Aerospace and Robotics:** Applications requiring precise speed and torque control.
- **Integrated Starter Generators:** In hybrid vehicles.

SRM drive control is a field of ongoing research and development, focusing on leveraging the inherent benefits of SRMs while addressing their drawbacks, particularly torque ripple and noise, to expand their applicability in demanding modern drive systems.

6.3. Stepper motor drivers

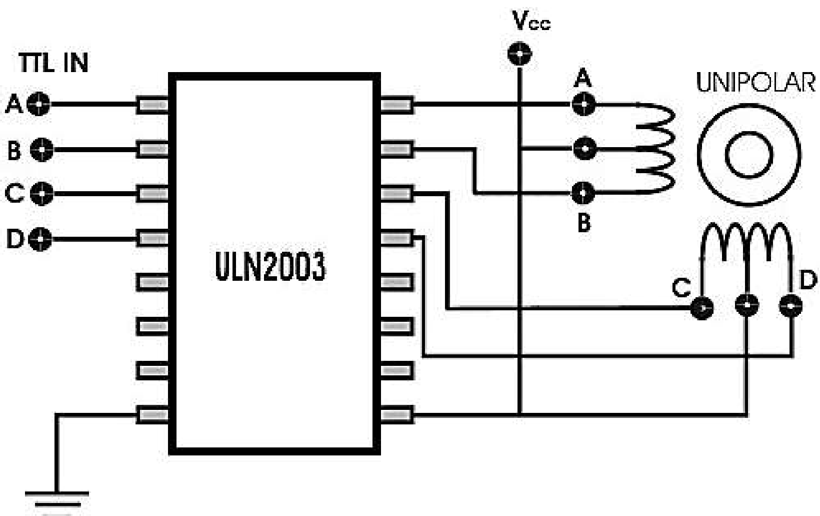


Figure 6-5. Motor driver circuit diagram

Stepper motor drivers are essential electronic devices that translate control signals from a microcontroller or other control system into the precise electrical pulses needed to make a stepper motor rotate in discrete steps. They are crucial because stepper motors require specific winding energization sequences and current control to achieve their precise movement.

6.3.1. Why are Stepper Motor Drivers Necessary?

- **Voltage and Current Control:** Microcontrollers typically cannot provide the necessary voltage and current levels to directly drive a stepper motor. Drivers amplify these signals.
- **Sequence Generation:** Stepper motors operate by energizing their windings in a specific sequence to create rotating magnetic fields. Drivers translate simple "step" and "direction" commands into these complex winding sequences.
- **Smooth Motion and Accuracy:** Drivers, especially those with micro stepping capabilities, divide the motor's full steps into smaller micro steps, leading to smoother motion, reduced vibration and noise, and increased positional accuracy.

6.3.2. Types of Stepper Motor Drivers:

Stepper motor drivers can be categorized based on several factors:

- **Motor Winding Arrangement:**
    - **Unipolar Drives:** Designed for unipolar stepper motors (typically 5, 6, or 8 leads with center-tapped coils). They simplify control by switching current from one coil to another within each phase, but generally produce less torque (around 30% less) as only half the windings are used at a time. Best for low-speed applications.
    - **Bipolar Drives:** Designed for bipolar stepper motors (typically 4, 6, or 8 leads without center taps). They achieve rotation by reversing the current direction in each phase, which requires a more complex H-bridge circuit but results in higher torque,

especially at low speeds (if wired in series) or high speeds (if wired in parallel).

- **Drive Circuitry:**
  - **L/R (Constant-Voltage) Drives:** Simpler and less costly. They apply a constant voltage to the windings. Performance can be limited, especially at higher speeds, as current rise time is dependent on the motor's inductance and resistance.
  - **Chopper (Constant-Current) Drives:** More complex and expensive but offer better performance. They regulate the current flowing through the motor windings, providing consistent torque output across a wider speed range and improving dynamic behavior. These are commonly used due to their superior performance and the availability of integrated circuits (ICs).
- **Step Mode:**
  - **Full-Step Mode:** The motor moves one full step per pulse. It's simple but can result in coarser movement and more vibration.
  - **Half-Step Mode:** Alternates between energizing one winding and two windings, effectively doubling the steps per revolution and providing smoother, more accurate movement than full-step mode.
  - **Micro stepping Mode:** Electronically divides each full step into even finer discrete angles (e.g., 1/4, 1/8, 1/16, 1/32, 1/256 of a full step). This significantly increases resolution, provides much smoother operation, reduces audible noise and vibration, and minimizes resonance effects. The trade-off can be a slight reduction in step accuracy under loaded conditions.
- **Control Interface:**
  - **Pulse/Direction (Step/Dir) Inputs:** The most common interface, where one input receives step pulses and another receives a direction signal.
  - **PWM Interface:** Directly controls the gate signals of the FETs in the H-bridge.
  - **Integrated Controller/Programmable Drives:** These drivers have a built-in microprocessor and can execute motion control

programs, offering advanced features like acceleration/deceleration ramping, conditional functions, and communication with other equipment.

6.3.3. Key Stepper Motor Driver ICs (Integrated Circuits):

Many manufacturers produce dedicated ICs for driving stepper motors, simplifying circuit design. Some popular examples include:

- **A4988:** A widely used, relatively low-cost micro stepping driver with a translator for easy control ($step/dir$ interface).
- **DRV8825:** Another popular micro stepping driver often considered an upgrade to the A4988, offering higher current capability and more micro step options.
- **TMC series (e.g., TMC2208, TMC2209):** Known for their "Stealth Chop" technology, which significantly reduces motor noise and provides very smooth operation, making them popular in 3D printers and quiet applications.
- **ULN2003:** A Darlington array IC commonly used for driving smaller unipolar stepper motors in full-step mode.
- **L298N:** A dual H-bridge driver that can control two DC motors or one bipolar stepper motor. It's often used in hobbyist projects.

Manufacturers like Allegro Microsystems, Texas Instruments (TI), and Microchip Technology offer extensive portfolios of stepper motor driver ICs with various features, current ratings, and voltage ranges.

6.3.4. How to Choose a Stepper Motor Driver:

Selecting the right driver is crucial for optimal system performance. Consider the following:

- **Motor Compatibility:**
  - **Type of Stepper Motor:** Unipolar or Bipolar. The driver must be compatible with your motor's winding configuration.
  - **Motor Current and Voltage:** The driver's continuous output

current and peak output current must meet or exceed the motor's requirements. The driver's supply voltage range should also be appropriate for the motor's rated voltage.

- **Performance Requirements:**
  - **Desired Resolution/Smoothness:** For applications requiring high precision and smooth motion (e.g., 3D printers, CNC machines), a micro stepping driver is essential.
  - **Speed and Torque:** Chopper drives generally offer better high-speed performance and more consistent torque.
  - **Noise and Vibration:** If quiet operation is critical, look for drivers with advanced algorithms like "Stealth Chop" or adaptive decay modes.
  - **Acceleration/Deceleration:** For moving heavier loads or achieving higher speeds, drivers with built-in ramping features can be beneficial.
- **Control and Interface:**
  - **Controller Compatibility:** Ensure the driver's input interface (e.g., $step/dir, PWM$) is compatible with your chosen microcontroller or control system.
  - **Programmability:** If advanced motion profiles or closed-loop control (with an encoder) are needed, consider programmable drivers.
- **Power Supply:** The power supply must provide sufficient voltage and current for both the driver and the motor.
- **Protection Features:** Look for drivers with built-in protection features such as overcurrent protection, thermal shutdown, and open-load/stall detection to protect the motor and the driver itself.

6.3.5. Applications of Stepper Motor Drivers:

Stepper motor drivers are integral to a wide range of applications requiring precise and repeatable motion control, including:

- **3D Printers:** For precise movement of the print head and bed.
- **CNC Machines:** Controlling cutting tools with high accuracy.

- **Robotics:** Enabling accurate angular positioning and movement of robotic arms and other components.
- **Medical Devices:** Used in surgical tools, diagnostic equipment, and fluid pumps where precision is paramount.
- **Industrial Automation:** Conveyor belts, pick-and-place machines, automated assembly lines.
- **Consumer Electronics:** Printers (paper feed, print head movement), scanners, cameras (focus/zoom).
- **Automotive:** Gauge clusters, headlight adjustment, air conditioning vents.
- **Vending Machines:** Dispensing products accurately.
- **Scientific Equipment:** Microscopes, telescopes, spectrometers for precise sample positioning.

6.3.6. Advantages and Disadvantages

The advantages and disadvantages of the stepper motor driver include the following.

- Battery drive
- Secure design
- Protection of Spark
- Protection of Thermal
- Mounting Space is small
- This motor driver is used to drive Unipolar Stepper Motors.
- By using this, we can evade expensive driver boards.

The disadvantages are

- The design of this driver is not an efficient one.
- It needs a lot of wiring for a tiny application.

6.4. Permanent Magnet Synchronous Motor (PMSM) drive control

Permanent Magnet Synchronous Motor (PMSM) drive control is a sophisticated and crucial aspect of modern electrical drive systems, enabling high performance, efficiency, and precise control for a wide range of applications, from electric vehicles to industrial automation and robotics.

Unlike traditional DC motors or induction motors, PMSMs utilize permanent magnets on the rotor, eliminating the need for rotor excitation current and thus reducing rotor losses and improving efficiency. However, this also introduces a challenge: the permanent magnet flux is constant and cannot be directly controlled like in wound-rotor machines. Therefore, effective control strategies are essential to manage the interaction between the stator's rotating magnetic field and the rotor's constant magnetic field.

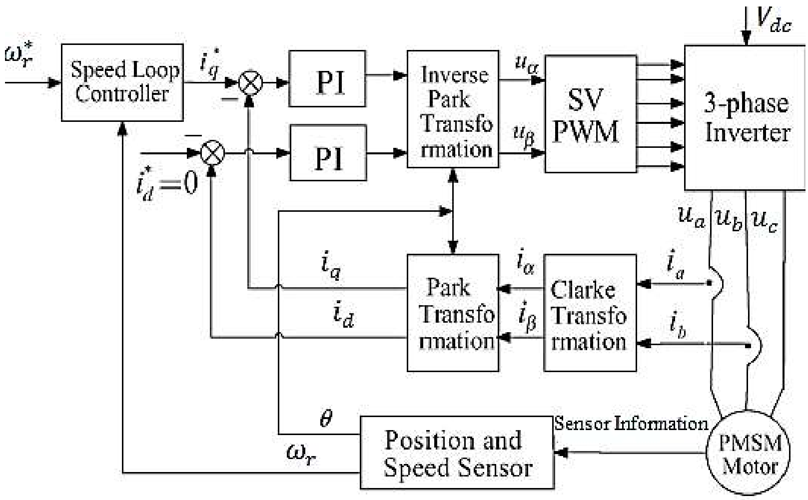


Figure 6-6. Block diagram of PMSM drive control

The primary goal of PMSM drive control is to achieve smooth rotation, full torque control (even at zero speed), fast acceleration/deceleration, and high efficiency across the entire operating range.

6.4.1. Fundamental Principles of PMSM Operation

Before diving into control, it's essential to understand the basic principles:

- **Rotor with Permanent Magnets:** The rotor of a PMSM has permanent magnets, creating a constant magnetic field.

- **Stator Windings:** The stator has three-phase windings, typically supplied with AC current to generate a rotating magnetic field.
- **Synchronous Operation:** The rotor's magnetic field locks in with the stator's rotating magnetic field, and the rotor rotates synchronously with the supply frequency.
- **Back EMF:** As the rotor rotates, it induces a sinusoidal back electromotive force (EMF) in the stator windings.
- **Torque Generation:** Torque is generated by the interaction of the stator's magnetic field and the rotor's permanent magnet field. For optimal torque, these two fields should be kept perpendicular to each other.

6.4.2. Key Challenges in PMSM Control

- **AC to DC Transformation:** PMSMs are AC machines, meaning the currents and voltages are sinusoidal and time-varying. For precise control, it's highly beneficial to convert these AC quantities into DC quantities in a rotating reference frame, simplifying the control problem.
- **Rotor Position Information:** To maintain the optimal alignment between stator and rotor fields, accurate knowledge of the rotor's instantaneous position is critical. This is typically achieved using position sensors (e.g., encoders, resolvers) or sensor less estimation techniques.
- **Decoupled Control:** To control torque and flux independently, similar to a separately excited DC motor, the stator current needs to be decomposed into two orthogonal components: one responsible for producing torque and the other for controlling flux.

6.4.3. Main Control Strategies

The most common and effective control strategies for PMSMs are:

6.4.3.1. Field-Oriented Control (FOC) / Vector Control

FOC is the most widely used and sophisticated control technique for high-performance PMSM drives. Its core idea is to transform the complex, coupled, and time-varying AC quantities in the stator's stationary reference frame into decoupled, constant DC quantities in a synchronously rotating reference frame aligned with the rotor's magnetic flux. This makes the control of a PMSM similar to that of a separately excited DC motor, where torque and flux can be controlled independently.

Steps Involved in FOC:

Measurement:

- **Stator Currents ($\boldsymbol{I_a, I_b, I_c}$)**: The three-phase stator currents are measured using current sensors.
- **Rotor Position ($\boldsymbol{\theta_e}$)**: The electrical rotor position is measured by a position sensor (e.g., encoder, resolver) or estimated using sensor less techniques. This is crucial for transformation.
- **Motor Speed ($\boldsymbol{\omega_m}$)**: Motor speed is derived from the rotor position.

Clarke Transformation ($\boldsymbol{abc\ to\ \alpha\beta}$): The three-phase ($abc$) stator currents are transformed into two-phase orthogonal stationary frame components (i_α, i_β). This simplifies the representation of the three-phase system.

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

(For balanced three-phase systems, i0 is zero and often omitted.)

Park Transformation ($\boldsymbol{\alpha\beta\ to\ dq}$): The stationary frame components (i_α, i_β) are then transformed into the synchronously rotating dq-frame components (i_d, i_q) using the rotor's electrical angle (θ_e).

- The **d-axis (direct axis)** is aligned with the rotor's permanent magnet flux. The current component id primarily controls the flux.
- The **q-axis (quadrature axis)** is perpendicular to the d-axis and directly contributes to torque production. The current component iq primarily

controls the torque.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \text{Sin}\,\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

PI Controllers:

- **Outer Speed Loop:** A Proportional-Integral (PI) controller compares the commanded speed (ω_{ref}) with the actual speed (ω_m) and generates the reference q-axis current (iq_{ref}). This is the primary torque command.
- **Inner Current Loops:** Two separate PI controllers regulate the d-axis and q-axis currents.
    - **d-axis current loop:** Compares actual id with reference id_{ref} (typically 0 for surface-mounted $PMSMs$ for maximum torque per ampere, or a negative value for interior $PMSMs$ for reluctance torque utilization and field weakening). It outputs the d-axis voltage command (vd_{ref}).
    - **q-axis current loop:** Compares actual iq with reference iq_{ref} (from the speed controller) and outputs the q-axis voltage command (vq_{ref}).

Inverse Park Transformation $(\boldsymbol{dq\ to\ \alpha\beta})$: The d-axis and q-axis voltage commands (vd_{ref}, vq_{ref}) are transformed back to the stationary $\alpha\beta$ frame $(v\alpha_{ref}, v\beta_{ref})$ using the same rotor electrical angle.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\text{Sin}\,\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

Space Vector Pulse Width Modulation (SVPWM): The αβ voltage commands $(v\alpha_{ref}, v\beta_{ref})$ are fed into an $SVPWM$ module. $SVPWM$ is a highly efficient and effective modulation technique for voltage source inverters $(VSIs)$. It calculates the switching times for the inverter's power switches $(e.g., IGBTs, MOSFETs)$ to generate the required three-phase AC voltages to the motor windings, synthesizing the desired rotating voltage vector.

Inverter: The VSI, controlled by the $SVPWM$ signals, converts the DC bus voltage into variable frequency and variable voltage AC power to drive the $PMSM$.

Advantages of $\boldsymbol{FOC}$:

- Excellent dynamic performance (fast response to changes in speed/torque).
- Precise torque and speed control.
- High efficiency due to decoupled control and optimal current waveforms.
- Allows for field weakening in IPMSMs to extend the speed range beyond the base speed.

Disadvantages of $\boldsymbol{FOC}$:

- Requires accurate rotor position information (sensor or robust sensor less estimation).
- Computationally intensive, requiring powerful microcontrollers or DSPs.
- Requires accurate motor parameters for optimal performance.

6.4.3.2. Direct Torque Control ($\boldsymbol{DTC}$)

DTC is another high-performance control strategy that directly controls the stator flux and electromagnetic torque without explicit current control loops or transformations to a rotating reference frame. It relies on instantaneous errors between reference and actual flux/torque to select appropriate voltage vectors from a lookup table.

Key Features of DTC:

- **Direct Control of Flux and Torque:** Measures stator voltage and current to estimate stator flux and electromagnetic torque.
- **Hysteresis Controllers:** Uses hysteresis comparators for torque and flux errors, which directly determine the switching state of the inverter.
- **Switching Table:** A switching table maps the outputs of the hysteresis controllers and the sector of the stator flux vector to the appropriate inverter switching states.
- **No Current Control Loops or $\boldsymbol{PWM}$:** Unlike FOC, DTC directly selects the voltage vectors without needing PWM modulators or inner current

loops.

Advantages of DTC:

- Very fast torque response.
- No need for Park/Clarke transformations or current regulators.
- Less dependent on motor parameters compared to FOC.
- Does not explicitly require a position sensor (though flux estimation requires some form of integration or estimation).

Disadvantages of DTC:

- Higher torque ripple and current ripple compared to FOC.
- Variable switching frequency, which can lead to audible noise and increased losses.
- Performance can degrade at very low speeds without advanced estimation techniques.

6.4.3.3. Scalar Control (V/f Control)

Scalar control, particularly $\frac{V}{f}$ (Voltage/Frequency) control, is the simplest method for controlling AC motors, including $PMSMs$, though it's primarily used for open-loop control or less demanding applications. The principle is to maintain a constant ratio of stator voltage to stator frequency ($\frac{V}{f}$) to keep the air gap flux constant.

How it Works:

- The frequency of the stator voltage determines the synchronous speed.
- The magnitude of the stator voltage is adjusted proportionally to the frequency to maintain a constant flux, ensuring that the motor produces sufficient torque.

Advantages of Scalar Control:

- Simple to implement.
- Does not require rotor position feedback (open-loop).

Disadvantages of Scalar Control:

- Poor dynamic performance.
- Limited speed and torque control range.
- Significant torque ripple, especially at low speeds.
- Not suitable for high-performance applications.

6.4.3.4. Advanced Control Concepts and Techniques

- **Sensor less Control:** Eliminates the need for physical position sensors by estimating the rotor position and speed using motor terminal voltages and currents. Common techniques include:
    - **Back EMF-based observers:** Effective at medium and high speeds.
    - **High-frequency injection methods:** Useful at very low and zero speeds for salient pole PMSMs (IPMSMs).
    - **Sliding Mode Observers (SMO), Extended Kalman Filters (EKF), Luenberger Observers:** More advanced estimation techniques.
- **Flux Weakening:** For interior permanent magnet synchronous motors (IPMSMs), where $Lq > Ld$, a negative d-axis current can be injected to "weaken" the flux and extend the operating speed range beyond the base speed (constant power region). This utilizes the reluctance torque component.
- **Maximum Torque Per Ampere (MTPA) Control:** For IPMSMs, MTPA control optimizes the d-q current references to produce the maximum possible torque for a given stator current magnitude, thereby maximizing efficiency in the constant torque region.
- **Model Predictive Control (MPC):** An advanced control strategy that uses a mathematical model of the PMSM to predict its future behavior. It then selects the optimal switching states of the inverter to minimize a defined cost function (e.g., minimizing current ripple, torque ripple, maximizing efficiency) over a prediction horizon. MPC offers excellent dynamic performance and can handle multiple control objectives.
- **Current and Voltage Limitations:** The control algorithms must account for the voltage and current limits of the inverter and the motor to prevent damage and ensure stable operation.

6.4.3.5. Hardware Components of a PMSM Drive System

A typical PMSM drive system consists of:

- **Power Supply:** Provides DC power to the inverter (often a rectified AC supply).
- **Inverter (VSI - Voltage Source Inverter):** Converts DC power into variable frequency and variable voltage AC power for the motor. It typically uses power semiconductor switches (IGBTs, MOSFETs) with fast switching capabilities.
- **PMSM Motor:** The permanent magnet synchronous motor itself.
- **Sensors:**
    - **Current Sensors:** To measure the phase currents.
    - **Position Sensor (Encoder/Resolver):** (For sensored FOC) To provide accurate rotor position feedback.
    - **Voltage Sensors:** To measure DC link voltage and sometimes phase voltages.
- **Control Unit (Microcontroller/DSP):** The "brain" of the drive. It implements the control algorithm (FOC, DTC, etc.), processes sensor feedback, calculates control commands, and generates PWM signals for the inverter. Modern digital signal controllers (DSCs) are specifically designed for motor control applications, offering high processing power and integrated motor control peripherals.
- **Gate Driver Circuit:** Amplifies the low-power control signals from the microcontroller to drive the high-power switches in the inverter.

PMSM drive control is a complex but highly rewarding field. Field-Oriented Control (FOC) remains the dominant technique for high-performance applications due to its precise control and high efficiency. Direct Torque Control (DTC) offers faster dynamics for certain applications. The continuous development of sensor less techniques, advanced control algorithms like MPC, and more powerful microcontrollers/DSPs is further expanding the capabilities and applicability of PMSM drives, making them increasingly popular in various industries requiring precise, efficient, and dynamic motion control.

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