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

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

COURSE MATERIAL

EE308 : ELECTRIC DRIVES

VISION OF THE INSTITUTION
To mould true citizens who are millennium leaders and catalysts of change through excellence in education.
MISSION OF THE INSTITUTION
NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values. We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2006
- Course offered: B.Tech Electrical and Electronics Engineering
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

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

DEPARTMENT MISSION

1. To offer quality education in Electrical and Electronics Engineering and prepare the students for professional career and higher studies.
2. To create research collaboration with industries for gaining knowledge about real-time problems.
3. To prepare students with sound technical knowledge.
4. To make students socially responsible.

PROGRAM OUTCOME (PO'S)

Engineering Graduates will be able to:

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

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

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

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

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

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

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

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

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

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

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

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

PROGRAM SPECIFIC OUTCOME(PSO'S)

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

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

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

COURSE OUTCOME

After the completion of the course the student will be able to

CO 1	To provide fundamental knowledge in dynamics and control of Electric Drives.
CO 2	To familiarize the various rectifier controlled DC motor drives.
CO 3	To familiarize the various chopper controlled DC motor drives.
CO 4	To familiarize the various semiconductor controlled Induction motor drives.
CO 5	To provide fundamental knowledge in Inverter fed AC drive and concept of vector control
CO 6	To familiarize the various semiconductor controlled synchronous motor drives.

CO VS PO'S AND PSO'S MAPPING

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO 1	PSO 2	PSO 3
CO 1	3	3	1	1	-	-	-	-	-	-	-	2	2	2	2
CO 2	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 3	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 4	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 5	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 6	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Module	Contents	Hours	Sem. Exam Marks
I	Introduction to electric drives – Block diagram – advantages of electric drives – Dynamics of motor load system, fundamental equations, and types of load – classification of load torque, four quadrant operation of drives. Steady state stability. Introduction to closed loop control of drives.	7	15%
II	DC motor drives- constant torque and constant power operation, separately excited dc motor drives using controlled rectifiers, single phase semi converter and single phase fully controlled converter drives. Three phase semi converter and fully controlled converter drives. Dual converters, applications of dual converter for speed control of DC motor. Closed loop control of separately excited dc motor drive. DC series motor drive for traction application.	7	15%
III	Chopper controlled DC drives. Analysis of single quadrant chopper drives. Regenerative braking control. Two quadrant chopper drives. Four quadrant chopper drives. Cycloconverters for drive applications – different types – basic principle.	7	15%
IV	Three phase induction motor speed control. Using semiconductor devices. Stator voltage control – stator frequency control - Stator voltage and frequency control (v/f). Rotor chopper speed control - slip power recovery control schemes – sub synchronous and super synchronous speed variations.	7	15%
V	Voltage source inverter fed induction motor drives, Current source inverter fed induction motor drives. Concept of space vector – Basic transformation in reference frame theory – field orientation principle.	7	20%
VI	Synchronous motor drives – introduction to v/f control. Permanent Magnet synchronous motor drives – different types – control requirements, converter circuits, modes of operation. Microcontroller based permanent magnet synchronous motor drives (schematic only).	7	20%

QUESTION BANK

MODULE I

1. What is an Electric Drive? Explain the function of each blocks with the help of a neat block diagram
2. Derive the fundamental torque equation of electric drive.
3. A motor-drive system has the following specifications:
   Polar moment of inertia of motor-load system referred to the shaft, J = 5 kg-m^2 , Motor torque T_m = 50 – 0.1N, and Load Torque, T_L = 0.025N, where, "N" is the speed of the motor in rpm. Calculate the start-up time of the drive.
4. Explain the four quadrant operation of electric drives.
5. What are the different components of a load torque? Explain each component in detail.
6. Differentiate between passive and active load torques. Give examples of each.
7. Derive the mathematical condition to obtain the steady state stability of equilibrium point.
8. With necessary diagrams explain in detail about the closed loop control.

MODULE II

1. Derive the speed torque characteristics of DC separately excited motor. Draw its speed torque characteristics for variable armature resistance.
2. Explain the armature voltage control and field weakening mode control of DC separately excited motor drive system.
3. Explain the speed control of separately excited DC motor using combined armature voltage and flux control method. Draw and explain the torque and power capability curves.
4. With a neat sketch, explain the motoring and braking operation of single phase fully controlled rectifier control of separately excited DC motor.
5. A 200 V, 875 rpm, 150 A separately excited dc motor has an armature resistance of 0.06Ω. It is fed from a single phase fully controlled rectifier with an ac voltage of 220 V,50Hz. Assuming continuous conduction, calculate (i) Firing angle for rated motor torque and 750 rpm (ii) Firing angle for rated motor torque and -500 rpm (iii) Motor speed for firing angle α=160o and rated torque
6. With a neat sketch, explain the motoring and braking operation of three phase half controlled rectifier control of separately excited DC motor.
7. With a neat sketch, explain the motoring and braking operation of three phase semiconverter control of separately excited DC motor.
8. With a neat sketch, explain the motoring and braking operation of three phase fully controlled rectifier control of separately excited DC motor.

9. A 220 V, 1500 rpm, 50 A separately excited motor with armature resistance of 0.5 Ω is fed from a three-phase fully controlled rectifier. Available ac source has a line voltage of 440 V, 50 Hz. A star-delta connected transformer is used to feed the armature so that motor terminal voltage equals rated voltage when the converter firing angle is zero. Determine the value of firing angle when: (a) motor is running at 1200 rpm and rated torque and (b) when motor is running at -800 rpm and twice the rated torque.
10. Draw and explain the speed torque curves of a fan load and traction load.

MODULE III

1. What are the different types of braking in DC motors? Why plugging is not popular. How the dynamic braking can be implemented by using a chopper.
2. With a chopper circuit and waveforms explain the regenerative braking of a DC motor drive.
3. With necessary diagrams explain class-A chopper fed DC motor.
4. With necessary diagrams explain class-C chopper fed DC motor.
5. Explain the operation of four quadrant chopper fed separately excited DC motor drive with necessary diagrams.
6. A 220 V, 900 rpm, 100 A separately excited DC motor has an armature resistance of 0.05 Ohm. It is braked by plugging from an initial speed of 1000 rpm. Calculate (i) Resistance to be placed in the armature circuit to limit braking current to 1.5 times the full load torque. (ii) Braking torque and (iii) Torque when the speed has fallen to zero.
7. A 230 V, 90 A, 500 rpm separately excited DC motor has an armature resistance of 0.15 Ω. The motor is controlled by a class-C chopper operating with a source voltage of 230 V and a frequency of 400 Hz. Calculate the motor speed for a braking operation at a duty ratio of 0.4 and half the rated torque.
8. A 230 V, 200 A, 960 rpm separately excited DC motor has an armature resistance of 0.02 Ω. The motor is fed from a class-C chopper. The DC input voltage to the chopper is 220 V. Braking method employed is dynamic braking using brake-chopper. The value of the braking resistor used is 2.5 Ω. Find the duty ratio of the brake-chopper if the speed is 700 rpm and braking torque is twice the rated torque of the motor.
9. Explain the basic principle of cycloconverter with necessary diagrams.
10. Explain the operation of step up cycloconverter with necessary diagrams.

MODULE – IV

1. Write short notes on different methods of speed control of Induction motor.
2. Make a comparison between Kramer and Scherbius system.
3. Mention the advantages of slip power recovery scheme over resistance control.
4. With necessary diagrams explain the Stator frequency control of an Induction

motor.

5. With necessary diagrams explain the Stator voltage and frequency control of an Induction motor.
6. With necessary diagrams explain the Stator voltage control of an Induction motor.
7. Explain the three modes of region in the adjustable frequency induction motor drives.
8. What do you meant by Slip power recovery scheme? Explain the Kramer system of an Induction motor drive.
    i) Conventional Method
    ii) Modified Method
    iii) Static Method(Open and Closed Loop)
9. What do you meant by Slip power recovery scheme? Explain the Scherbius system of an Induction motor drive.
    i) Conventional Method
    ii) Static Method(Open and Closed Loop)
10. Explain the rotor resistance controlled Induction motor drive.
    i) Conventional Method
    ii) Static Method(Open and Closed Loop)
11. Explain the Cycloconverter Scherbius system of an Induction motor drive.
12. Explain the Sub synchronous and super synchronous operation of an Induction motor drive.
13. What is slip power recovery scheme? Describe static Scherbius drive and show that the slip at which it operates is given by $S = -(a_T/a)\cos\alpha$, where ‘a’ and ’a_T‘ pertain to per phase turns ratio for induction motor and transformer respectively. Why it is always suggested to use a transformer in line side converter for static Scherbius drive?

MODULE – V

1. Write a note on various schemes of VSI fed Induction Motor Drives.
2. Write a note on various schemes of CSI fed Induction Motor Drives.
3. Write a note on Cycloconverter fed Induction Motor Drives.
4. Write a note on closed loop control of VSI fed Induction Motor Drives.
5. Write a note on closed loop control of CSI fed Induction Motor Drives.
6. With necessary diagram explain the CSI fed induction motor drive.
7. Give a note on Field Oriented control.
8. Give a note on vector control of induction motor drive.
9. Give a brief note on Space vector modulation.
10. Compare VSI fed induction motor with CSI fed induction motor drives.
11. Explain the frame transformation from three phase to synchronous reference frame. What

is its significance in induction motor drive?

12. Compare CSI fed IM drive with VSI fed IM drive.

MODULE – VI

1. With necessary diagram explain the True Synchronous mode of Synchronous motor drive.
2. With necessary diagram explain the Self Synchronous mode of Synchronous motor drive.
3. With necessary diagram explain the VSI fed Synchronous motor drive.
4. With necessary diagram explain the CSI fed Synchronous motor drive.
5. Give a note on different types of Synchronous motor drive.
6. Give a note on control strategies employed in PMSM drive.
7. Give a note on converter circuit of PMSM drive.
8. Compare Sinusoidal PMAC motor with Trapezoidal PMAC motor drives.
9. Explain the operation of Sinusoidal PMAC Motor drive.
10. Explain the operation of Trapezoidal PMAC Motor drive.
11. Explain the operation of Brushless DC Motor drive.
12. Explain the operation of Permanent Magnet Synchronous Motor drive.
13. Explain the operation of microcontroller based Permanent Magnet Synchronous Motor drive.
14. Explain the self-controlled synchronous motor drive employing load commutated thyristor inverter along with the diagram.

UNIT – I CHARACTERISTICS OF ELECTRIC DRIVES

Speed - Torque characteristics of various types of loads and drive motors - Joint speed -Torque characteristics - Selection of power rating for drive motors with regard to thermal overloading and load variation factors – load equalization – Starting, braking, and reversing operations.

Objectives

- To study the characteristics of various types of electric motors and different types of loads.
- To study the selection of power rating of a motor for various applications.
- To study the starting, braking and reversing operations of various types of motors.

Introduction

This units deals with the selection electrical motor for various types of applications based on the requirement of load on various aspects like electrical characteristics, mechanical characteristics, atmospheric conditions etc. Starting and braking of various electrical motor is very much essential for each and every drive selection. Reversing operation is also essential for certain type of drives. Hence by completing this unit the reader should get the knowledge about various types of load and its characteristics, various types of motor and its characteristics, the drive selection for different application and the static and dynamic operation

Electrical Drives:

Motion control is required in large number of industrial and domestic applications like transportation systems, rolling mills, paper machines, textile mills, machine tools, fans, pumps, robots, washing machines etc.

Systems employed for motion control are called **DRIVES**, and may employ any of prime movers such as diesel or petrol engines, gas or steam turbines, steam engines, hydraulic motors and electric motors, for supplying mechanical energy for motion control. Drives employing electric motors are known as **ELECTRICAL DRIVES**.

An **ELECTRIC DRIVE** can be defined as an electromechanical device for converting electrical energy into mechanical energy to impart motion to different machines and mechanisms for various kinds of process control.

Classification of Electric Drives

According to Mode of Operation

- Continuous duty drives
- Short time duty drives
- Intermittent duty drives

According to Means of Control

- Manual
- Semi automatic
- Automatic

According to Number of machines

- Individual drive
- Group drive
- Multi-motor drive

According to Dynamics and Transients

- Uncontrolled transient period
- Controlled transient period

According to Methods of Speed Control

- Reversible and non-reversible uncontrolled constant speed.
- Reversible and non-reversible step speed control.
- Variable position control.
- Reversible and non-reversible smooth speed control.

Advantages of Electrical Drive

1. They have flexible control characteristics. The steady state and dynamic characteristics of electric drives can be shaped to satisfy the load requirements.
2. Drives can be provided with automatic fault detection systems. Programmable logic controller and computers can be employed to automatically control the drive operations in a desired sequence.
3. They are available in wide range of torque, speed and power.
4. They are adaptable to almost any operating conditions such as explosive and radioactive environments
5. It can operate in all the four quadrants of speed-torque plane

6. They can be started instantly and can immediately be fully loaded
7. Control gear requirement for speed control, starting and braking is usually simple and easy to operate.

Choice (or) Selection of Electrical Drives

Choice of an electric drive depends on a number of factors. Some of the important factors are

1. Steady State Operating conditions requirements

   Nature of speed torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrants of operation, speed fluctuations if any, ratings etc

2. Transient operation requirements

   Values of acceleration and deceleration, starting, braking and reversing performance.

3. Requirements related to the source

   Types of source and its capacity, magnitude of voltage, voltage fluctuations, power factor, harmonics and their effect on other loads, ability to accept regenerative power

4. Capital and running cost, maintenance needs life.
5. Space and weight restriction if any.
6. Environment and location.
7. Reliability.

Group Electric Drive

This drive consists of a single motor, which drives one or more line shafts supported on bearings. The line shaft may be fitted with either pulleys and belts or gears, by means of which a group of machines or mechanisms may be operated. It is also sometimes called as SHAFT DRIVES.

Advantages

A single large motor can be used instead of number of small motors

Disadvantages

There is no flexibility. If the single motor used develops fault, the whole process will be stopped.

Individual Electric Drive

In this drive each individual machine is driven by a separate motor. This motor also imparts motion to various parts of the machine.

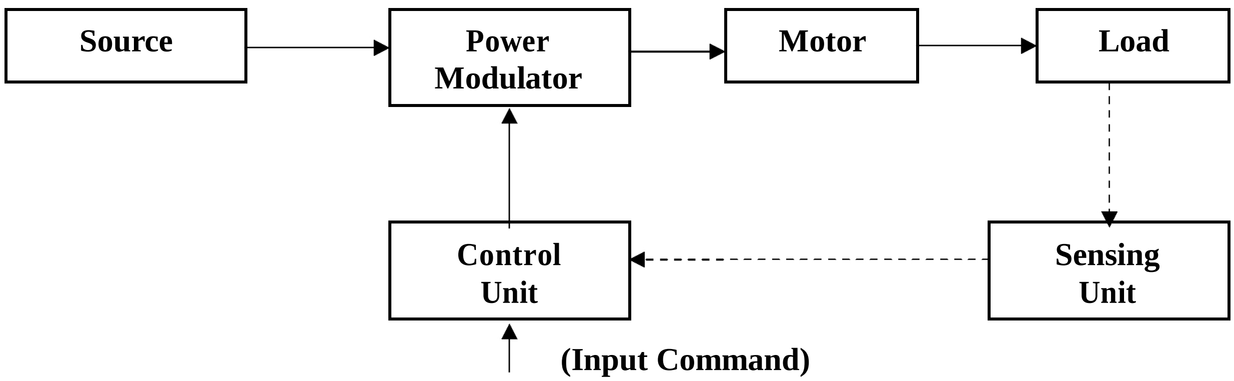
Multi Motor Electric Drive

In this drive system, there are several drives, each of which serves to actuate one of the working parts of the drive mechanisms.

E.g.: Complicated metal cutting machine
tools Paper making industries,
Rolling machines etc.

General Electric Drive System

Block diagram of an electric drive system is shown in the figure below.



A modern variable speed electrical drive system has the following components

- Electrical machines and loads
- Power Modulator
- Sources
- Control unit
- Sensing unit

Electrical Machines

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

DC Machines

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

AC Machines

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

Special Machines

Brush less DC motors, stepper motors, switched reluctance motors are used.

Power Modulators

Functions

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

Types of Power Modulators

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

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

Electrical Sources

Very low power drives are generally fed from single phase sources. Rest of the drives is powered from a 3 phase source. Low and medium power motors are fed from a 400v supply. For higher ratings, motors may be rated at 3.3KV, 6.6KV and 11 KV. Some drives are powered from battery.

Sensing Unit

- Torque Sensing
- Position Sensing
- Speed Sensing (From motor)

Current sensing and Voltage Sensing from Lines or from motor terminals

From Load

- Torque sensing
- Temperature Sensing

Control Unit

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

Classification of Electrical Drives

Another main classification of electric drive is

- DC drive
- AC drive

Comparison between DC and AC drives

DC DRIVES	AC DRIVES
The power circuit and control circuit is simple and inexpensive	The power circuit and control circuit are complex
It requires frequent maintenance	Less Maintenance
The commutator makes the motor bulky, costly and heavy	These problems are not there in these motors and are inexpensive, particularly squirrel cage induction motors
Fast response and wide speed range of control, can be achieved smoothly by conventional and solid state control	In solid state control the speed range is wide and conventional method is stepped and limited
Speed and design ratings are limited Due to communications.	Speed and design ratings have upper limits

Applications

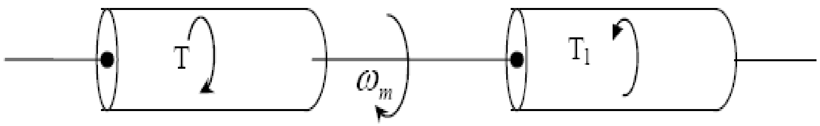
Paper mills
Cement Mills
Textile mills
Sugar Mills
Steel Mills
Electric Traction
Petrochemical Industries
Electrical Vehicles

Dynamics of Motor Load System

Fundamentals of Torque Equations

A motor generally drives a load (Machines) through some transmission system. While motor always rotates, the load may rotate or undergo a translational motion.

Load speed may be different from that of motor, and if the load has many parts, their speed may be different and while some parts rotate others may go through a translational motion. Equivalent rotational system of motor and load is shown in the figure.



Notations Used:

J = Moment of inertia of motor load system referred to the motor shaft $kg - m^2$

ω_m = Instantaneous angular velocity of motor shaft, rad/sec.

T = Instantaneous value of developed motor torque, N-m

T_l = Instantaneous value of load torque, referred to the motor shaft N-m

Load torque includes friction and wind age torque of motor. Motor-load system shown in figure can be described by the following fundamental torque equation.

$$T - T_l = \frac{d}{dt}(J\omega_m) = J\frac{d\omega_m}{dt} + \omega_m\frac{dJ}{dt} ------------(1)$$

Equation (1) is applicable to variable inertia drives such as mine winders, reel drives, Industrial robots.

For drives with constant inertia $\frac{dJ}{dt} = 0$

$$\therefore T = T_l + J\frac{d\omega_m}{dt} ------------(2)$$

Equation (2) shows that torque developed by motor is counter balanced by load torque T_l and a dynamic torque $\left(J\frac{d\omega_m}{dt}\right)$. Torque component $\left(J\frac{d\omega_m}{dt}\right)$ is called dynamic torque because it is present only during the transient operations.

Note:

Energy associated with dynamic torque $\left(J\frac{d\omega_m}{dt}\right)$ is stored in the form of kinetic energy given by $\frac{J\omega_m^2}{2}$.

Components of Load Torques:

The load torque T_l can be further divided in to following components

(i) Friction Torque (T_F)

Friction will be present at the motor shaft and also in various parts of the load. T_F is the equivalent value of various friction torques referred to the motor shaft.

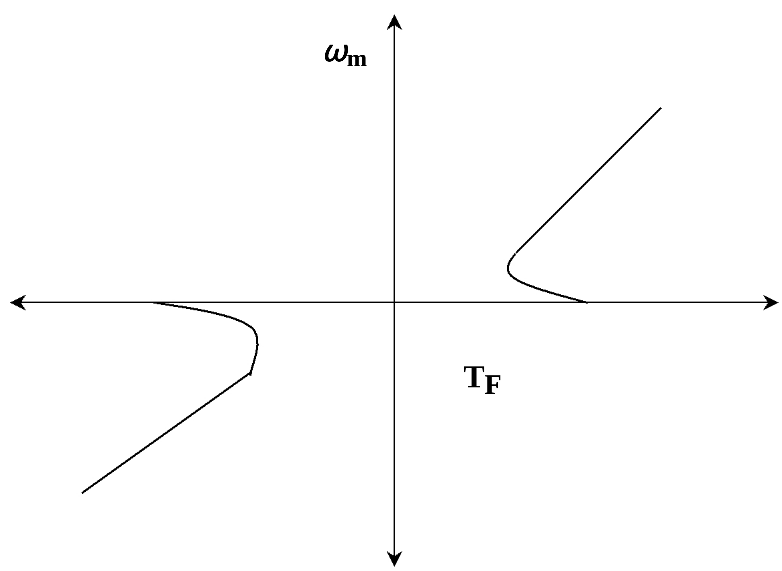
(ii) Windage Torque (T_W)

When motor runs, wind generates a torque opposing the motion. This is known as windage torque.

(iii) Torque required to do useful mechanical work.

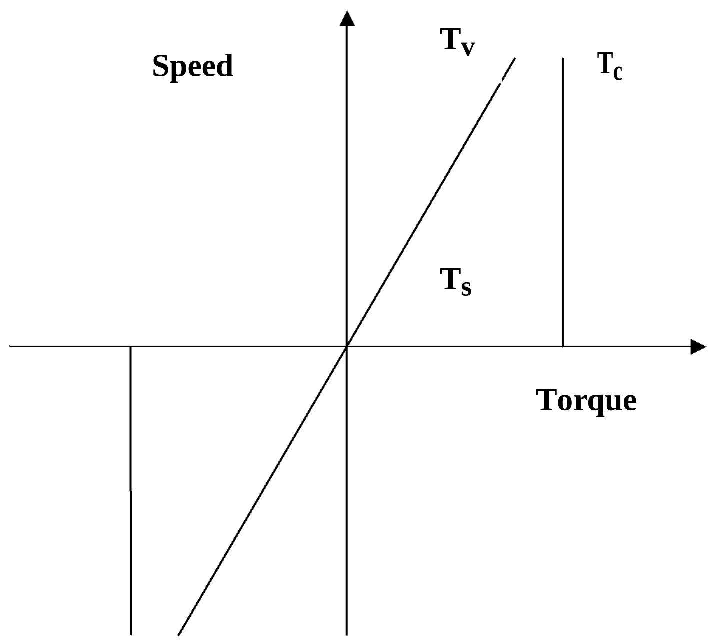
Nature of this torque depends upon particular application. It may be constant and independent of speed. It may be some function of speed, it may be time invariant or time variant, its nature may also change with the load's mode of operation.

Value of friction torque with speed is shown in figure below



Its value at stand still is much higher than its value slightly above zero speed. Friction at zero speed is called stiction or static friction. In order to start the drive the motor should at least exceed stiction.

Friction torque can also be resolved into three components



Component T_V varies linearly with speed is called VISCOUS friction and is given by

$$T_v = B\omega_m$$

Where B is viscous friction co-efficient.

Another component T_C, which is independent of speed, is known as COULOMB friction. Third component T_s accounts for additional torque present at stand still. Since Ts is present only at stand still it is not taken into account in the dynamic analysis. Windage torque, T_W which is proportional to speed squared is given by

$$T_w = C\omega_m^{\ 2} \qquad \text{C is a constant}$$

From the above discussions, for finite speed

$$T_l = T_L + B\omega_m + T_C + C\omega_m^{\ 2}$$

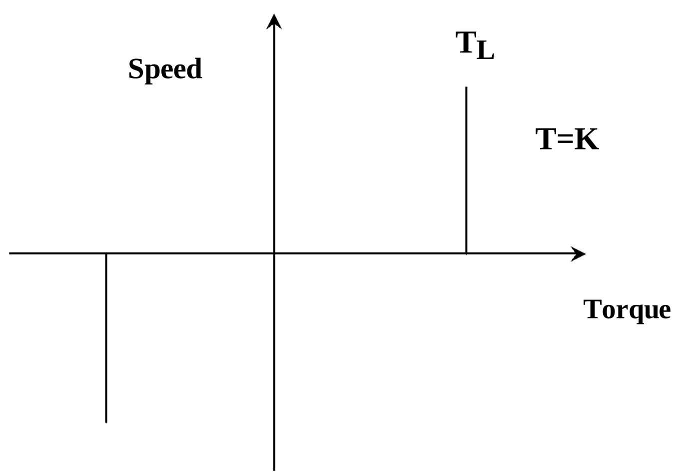
Characteristics of Different types of Loads

One of the essential requirements in the section of a particular type of motor for driving a machine is the matching of speed-torque characteristics of the given drive unit and that of the motor. Therefore the knowledge of how the load torque varies with speed of the driven machine is necessary. Different types of loads exhibit different speed torque characteristics. However, most of the industrial loads can be classified into the following four categories.

- **Constant torque type load**
- **Torque proportional to speed (Generator Type load)**
- **Torque proportional to square of the speed (Fan type load)**
- **Torque inversely proportional to speed (Constant power type load)**

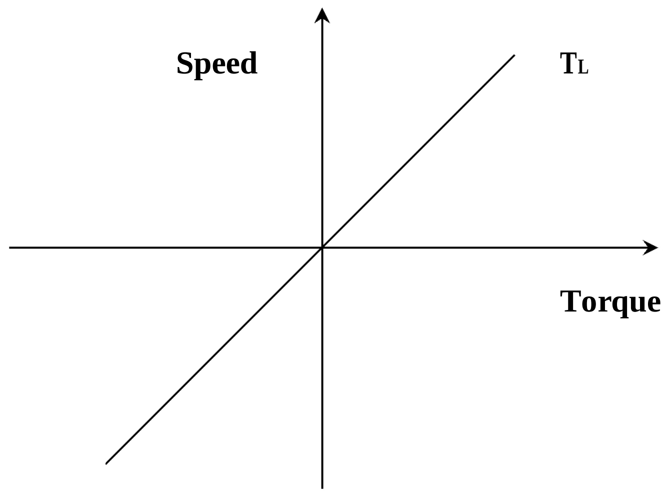
Constant Torque characteristics:

Most of the working machines that have mechanical nature of work like shaping, cutting, grinding or shearing, require constant torque irrespective of speed. Similarly cranes during the hoisting and conveyors handling constant weight of material per unit time also exhibit this type of characteristics.



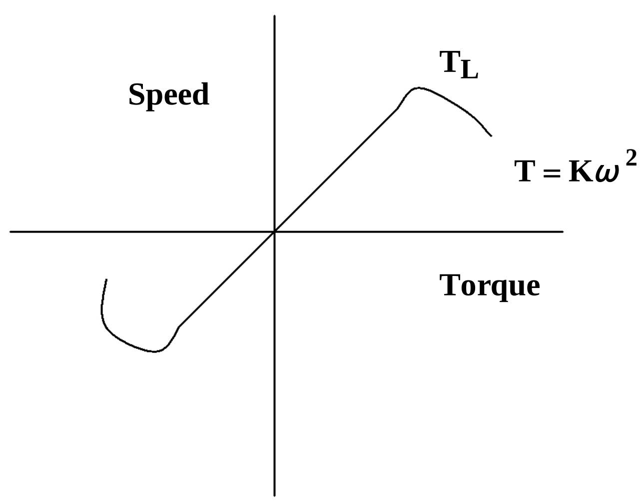
Torque Proportional to speed:

Separately excited dc generators connected to a constant resistance load, eddy current brakes have speed torque characteristics given by T=kω



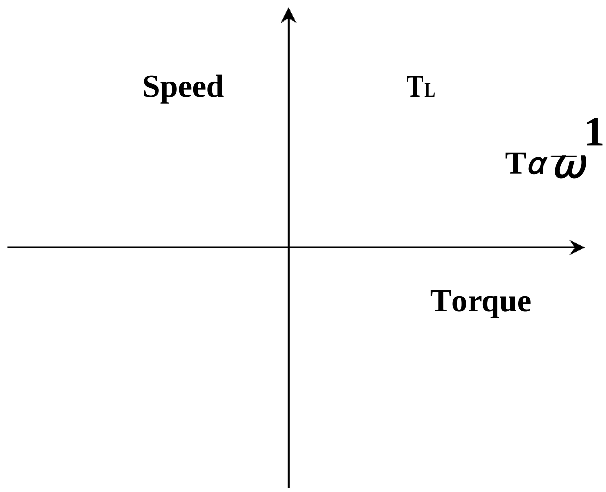
Torque proportional to square of the speed:

Another type of load met in practice is the one in which load torque is proportional to the square of the speed.Eg Fans rotary pumps, compressors and ship propellers.



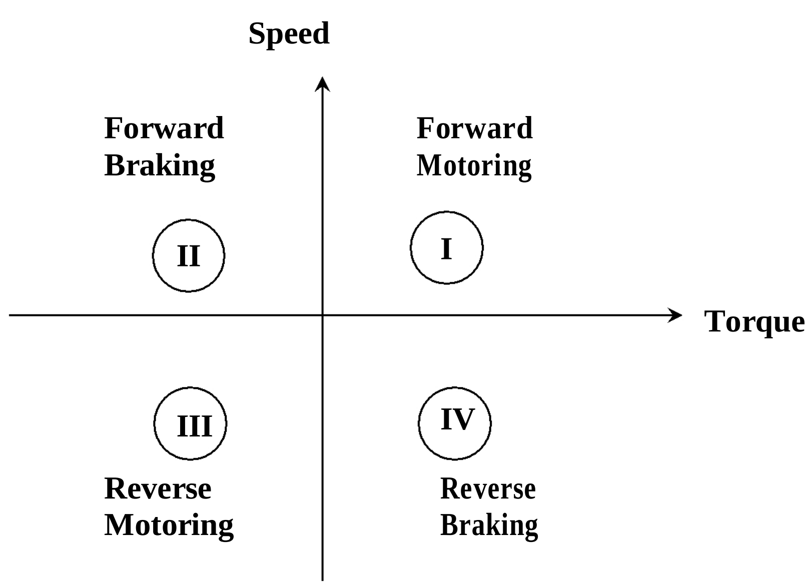
Torque Inversely proportional to speed:

Certain types of lathes, boring machines, milling machines, steel mill coiler and electric traction load exhibit hyperbolic speed-torque characteristics

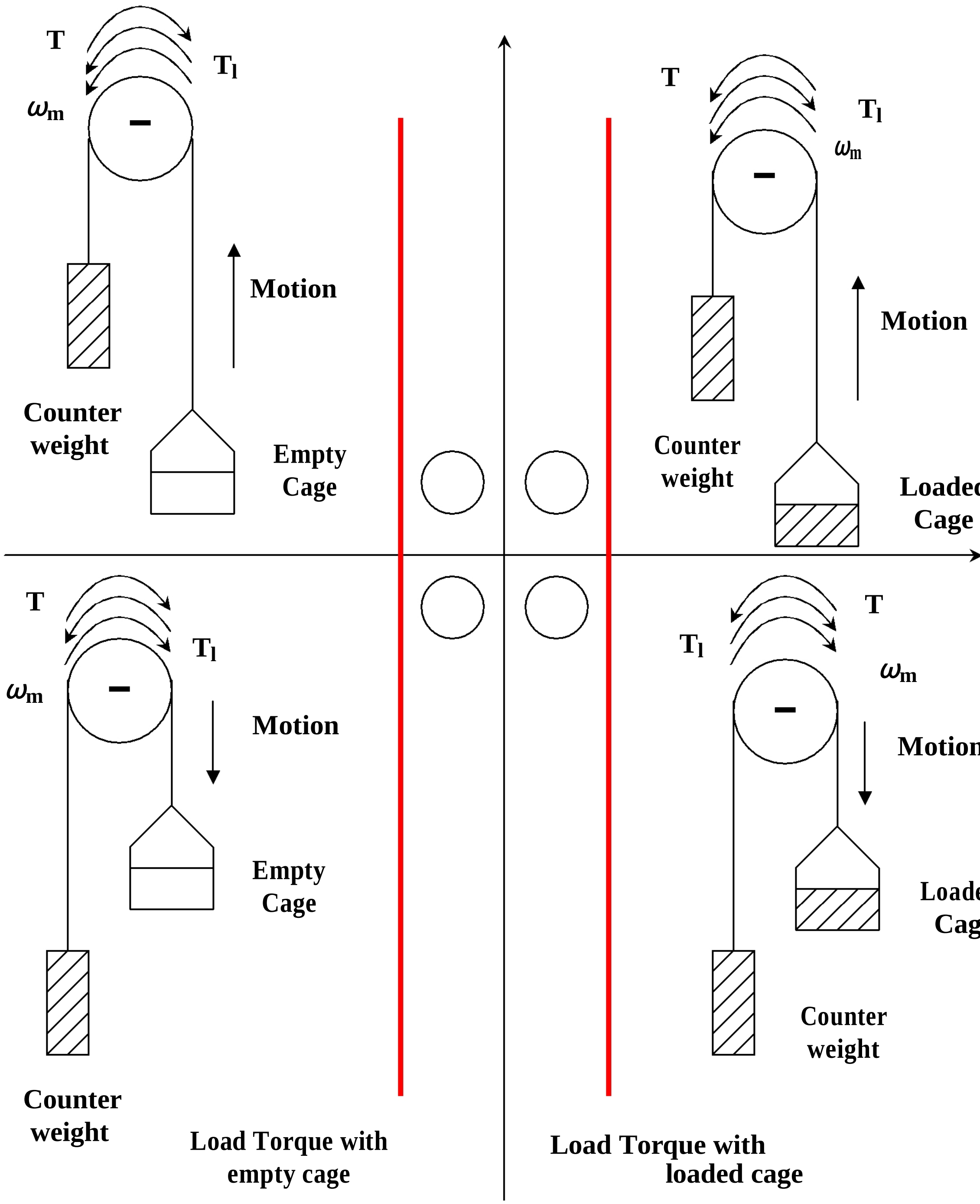


Multi quadrant Operation:

For consideration of multi quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed. A motor operates in two modes – Motoring and braking. In motoring, it converts electrical energy into mechanical energy, which supports its motion. In braking it works as a generator converting mechanical energy into electrical energy and thus opposes the motion. Motor can provide motoring and braking operations for both forward and reverse directions. Figure shows the torque and speed co-ordinates for both forward and reverse motions. Power developed by a motor is given by the product of speed and torque. For motoring operations power developed is positive and for braking operations power developed is negative.



In quadrant I, developed power is positive, hence machine works as a motor supplying mechanical energy. Operation in quadrant I is therefore called Forward Motoring. In quadrant II, power developed is negative. Hence, machine works under braking opposing the motion. Therefore operation in quadrant II is known as forward braking. Similarly operation in quadrant III and IV can be identified as reverse motoring and reverse braking since speed in these quadrants is negative. For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction of motor and load torques and direction of speed are marked by arrows.



A hoist consists of a rope wound on a drum coupled to the motor shaft one end of the rope is tied to a cage which is used to transport man or material from one level to another level . Other end of the rope has a counter weight. Weight of the counter weight is chosen to be higher than the weight of empty cage but lower than of a fully loaded cage. Forward direction of motor speed will be one which gives upward motion of the cage. Load torque line in quadrants I and IV represents speed-torque characteristics of the loaded hoist. This torque is the difference of torques due to loaded hoist and counter weight.

The load torque in quadrants II and III is the speed torque characteristics for an empty hoist. This torque is the difference of torques due to counter weight and the empty hoist. Its sigh is negative because the counter weight is always higher than that of an empty cage.

The quadrant I operation of a hoist requires movement of cage upward, which corresponds to the positive motor speed which is in counter clockwise direction here. This motion will be obtained if the motor products positive torque in CCW direction equal to the magnitude of load torque T_{L1}. Since developed power is positive, this is forward motoring operation. Quadrant IV is obtained when a loaded cage is lowered. Since the weight of the loaded cage is higher than that of the counter weight .It is able to overcome due to gravity itself.

In order to limit the cage within a safe value, motor must produce a positive torque T equal to T_{L2} in anticlockwise direction. As both power and speed are negative, drive is operating in reverse braking operation. Operation in quadrant II is obtained when an empty cage is moved up. Since a counter weigh is heavier than an empty cage, its able to pull it up. In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{L2} in clockwise direction. Since speed is positive and developed power is negative, it's forward braking operation.

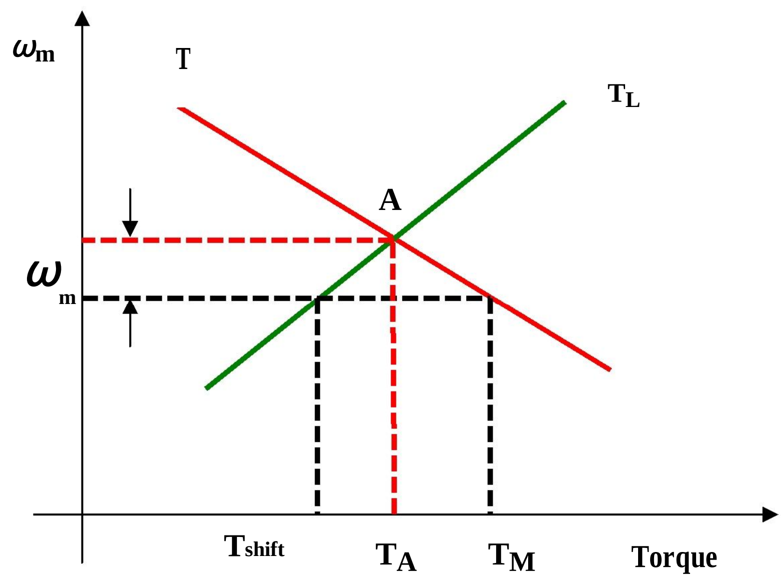
Operation in quadrant III is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in CW direction. Since speed is negative and developed power is positive, this is reverse motoring operation.

Steady State Stability:

Equilibrium speed of motor-load system can be obtained when motor torque equals the load torque. Electric drive system will operate in steady state at this speed, provided it is the speed of stable state equilibrium. Concept of steady state stability has been developed to readily evaluate the stability of an equilibrium point from the steady state speed torque curves of the motor and load system.

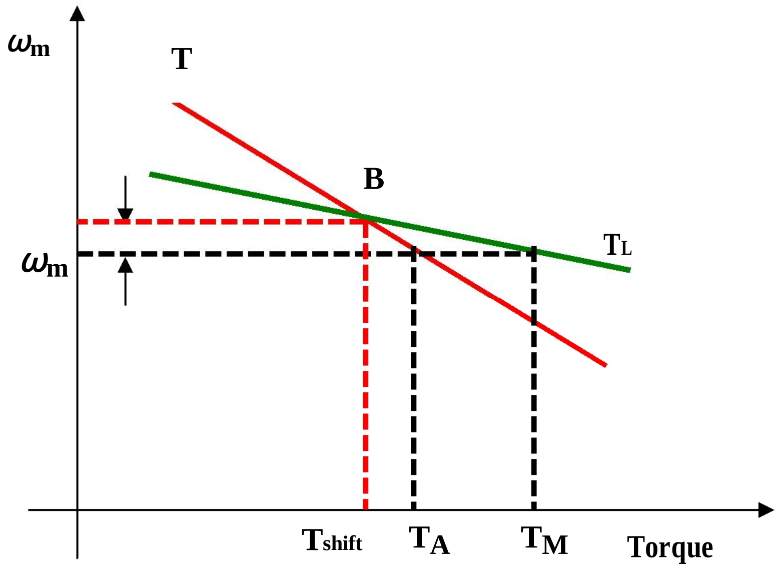
In most of the electrical drives, the electrical time constant of the motor is negligible compared with the mechanical time constant. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient state operation.

Now, consider the steady state equilibrium point A shown in figure below



The equilibrium point will be termed as stable state when the operation will be restored to it after a small departure from it due to disturbance in the motor or load. Due to disturbance a reduction of ω_m in speed at new speed, electrical motor torque is greater than the load torque, consequently motor will accelerate and operation will be restores to point A. similarly an increase in ω_m speed caused by a disturbance will make load torque greater than the motor torque, resulting into deceleration and restoring of operation to point A.

Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure. A decrease in speed causes the load torque to become greater than the motor torque, electric drive decelerates and operating point moves away from point B. Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B



From the above discussions, an equilibrium point will be stable when an increase in speed causes load-torque to exceed the motor torque. (i.e.) When at equilibrium point following conditions is satisfied.

$$\frac{dT_L}{d\omega_m} > \frac{dT}{d\omega_m} \text{-----------------} (1)$$

Inequality in the above equation can be derived by an alternative approach. Let a small perturbation in speed, ω_m results in T and T_l perturbation in T and T_l respectively. Therefore the general load-torque equation becomes

$$(T + T) = (T_l + T_l) + \frac{Jd(\omega_m + \omega_m)}{dt}$$

$$= T + T = T_l + T_l + \frac{Jd\omega_m}{dt} + J\frac{d\ \omega_m}{dt} \text{----} (2)$$

The general equation is

$$T = T_l + J\frac{d\omega}{dt} \text{'''} \text{-------} (3)$$

Subtracting (3) from (2) and rearranging

$$J\frac{d\omega_m}{dt} = T - T_l \text{-----------} (4)$$

From small perturbations, the speed –torque curves of the motor and load can be assumed to be straight lines, thus

$$T = \frac{dT}{d\omega_m}\omega_m \text{ - - - - - - - (5)}$$

$$T_l = \frac{dT_l}{d\omega_m}\omega_m \text{ - - - - - - - (6)}$$

Where $\frac{dT}{d\omega_m}$ and $\frac{dT}{d\omega_m}$ are respectively slopes of the steady state speed torque curves of motor and load at operating point under considerations. Substituting (5) and (6) in (4) we get,

$$J\frac{d\omega_m}{dt} + \left(\frac{dT_l}{d\omega_m} - \frac{dT}{d\omega_m}\right)\omega_m = 0 \text{ - - - - - (7)}$$

This is a first order linear differential equation. If initial deviation in speed at t=0 be $(\omega_m)_0$ then the solution of equation (7) is

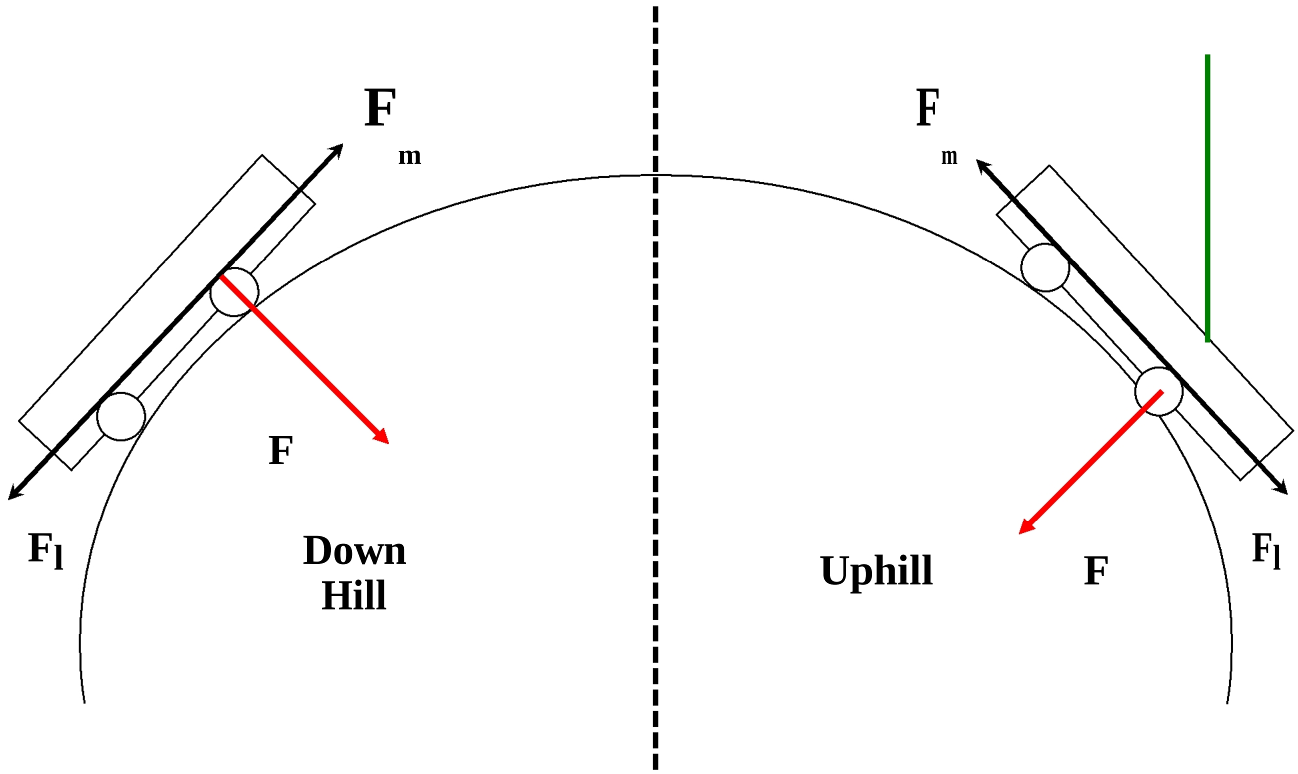
$$\omega_m = (\omega_m)_0 \exp -\frac{1}{J}\left(\frac{dT_l}{d\omega_m} - \frac{dT}{d\omega_m}\right)t \text{ - - - - - (8)}$$

An operating point will be stable when ω_m approaches zero as t approaches infinity. For this to happen exponential term in equation (8) should be negative.

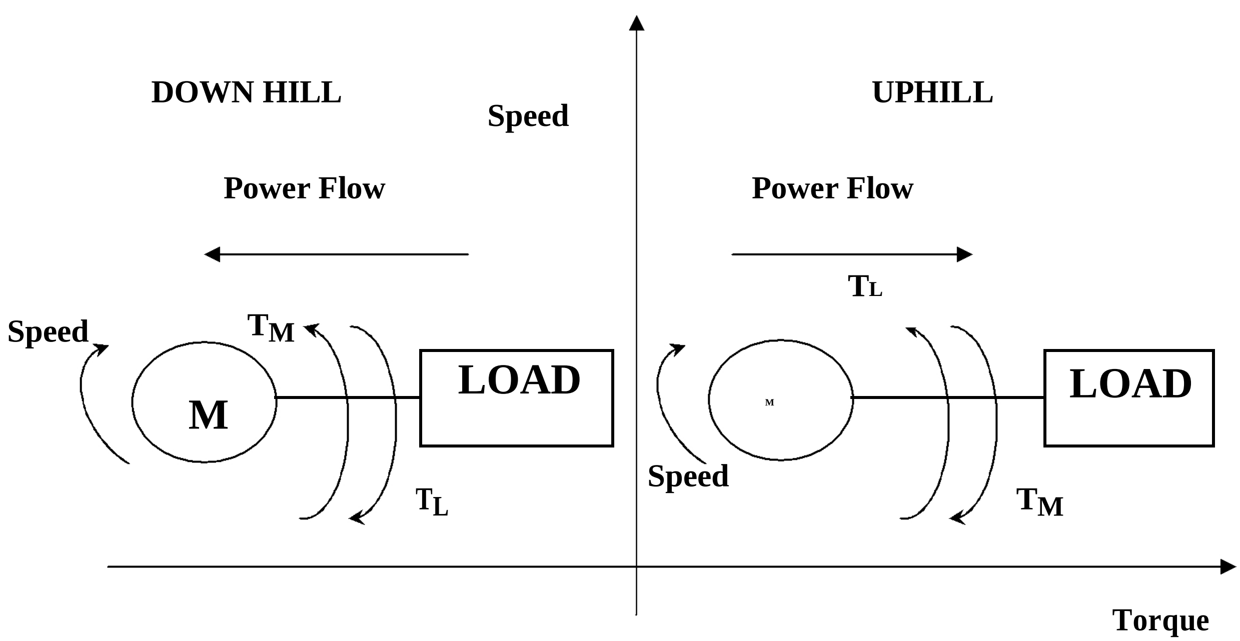
Basics of Regenerative Braking

In the regenerative braking operation, the motor operates as generator, while it is still connected to the supply. Here, the motor speed is greater than the synchronous speed. Mechanical energy is converted into electrical energy, part of which is returned to the supply and rest of the energy is last as heat in the winding and bearings of electrical machines pass smoothly from motoring region to generating region, when over driven by the load.

An example of regenerative braking is shown in the figure below. Here an electric motor is driving a trolley bus in the uphill and downhill direction. The gravity force can be resolved into two components in the uphill direction. One is perpendicular to the load surface (F) and another one is parallel to the road surface F_l. The parallel force pulls the motor towards bottom of the hill. If we neglect the rotational losses, the motor must produce force F_m opposite to F_l to move the bus in the uphill direction.



This operation is indicated as shown in the figure below in the first quadrant. Here the power flow is from the motor to load.



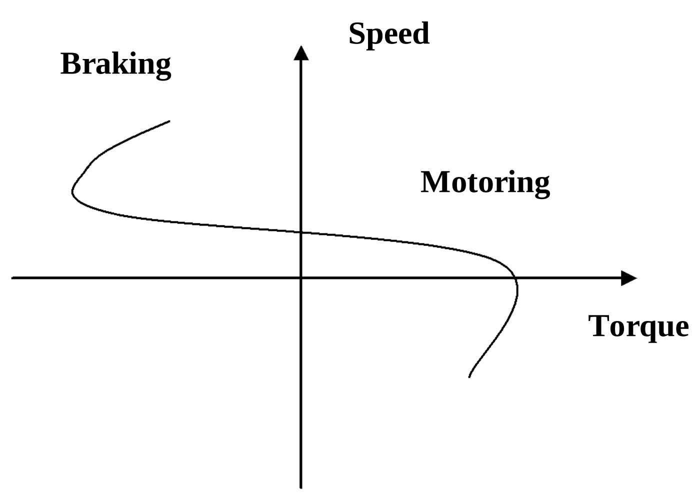
Now we consider that the same bus is traveling in down hill, the gravitational force doesn't change its direction but the load torque pushes the motor towards the bottom of the hill. The motor produces a torque in the reverse direction because the direction of the motor torque is always opposite to the direction of the load torque. Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power flows from mechanical load to source. Hence, the load is driving the machine and the machine is generating electric power that is returned to the supply.

Regenerative braking of Induction motor:

An induction motor is subjected to regenerative braking, if the motor rotates in the same direction as that of the stator magnetic field, but with a speed greater than the synchronous speed. Such a state occurs during any one of the following process.

- **Downward motion of a loaded hoisting mechanism**
- **During flux weakening mode of operation of IM.**

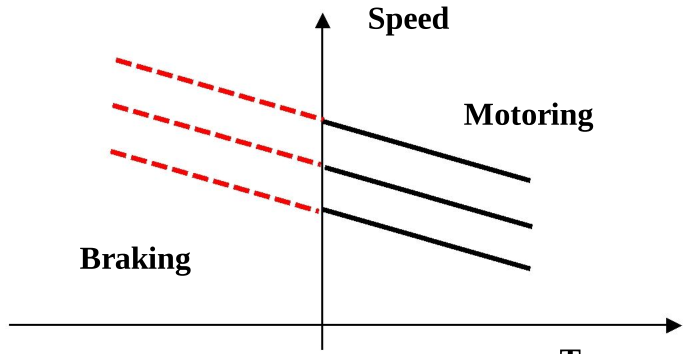
Under regenerative braking mode, the machine acts as an induction generator. The induction generator generates electric power and this power is fed back to the supply. This machine takes only the reactive power for excitation. The speed torque characteristic of the motor for regenerative braking is shown in the figure.



Regenerative Braking for DC motor:

In regenerative braking of dc motor, generated energy is supplied to the source. For this the following condition is to be satisfied.

$$E > V \text{ and } I_a \text{ should be negative}$$



Modes of Operation:

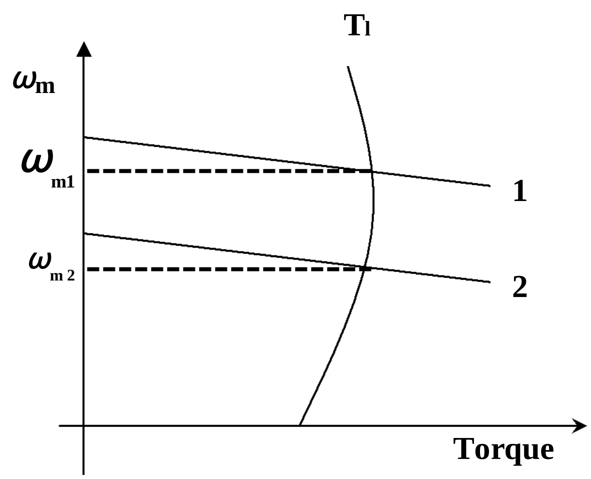
An electrical drive operates in three modes:

- **Steady state**
- **Acceleration including Starting**
- **Deceleration including Stopping**

We know that $T = T_l + J\dfrac{d\omega_m}{dt}$

According to the above expression the steady state operation takes place when motor torque equals the load torque. The steady state operation for a given speed is realized by adjustment of steady state motor speed torque curve such that the motor and load torques are equal at this speed. Change in speed is achieved by varying the steady state motor speed torque curve so that motor torque equals the load torque at the new desired speed. In the figure shown below when the motor parameters are adjusted to provide speed torque curve 1, drive runs at the desired speed ω_{m1} **. Speed is changed to** ω_{m2} **when the motor parameters are adjusted to provide speed torque curve 2. When load torque opposes motion, the motor works as a motor operating in quadrant I or III depending on the direction of rotation. When the load is active it can reverse its sign and act to assist the motion. Steady state operation for such a case can be obtained by adding a mechanical brake which will produce a torque in**

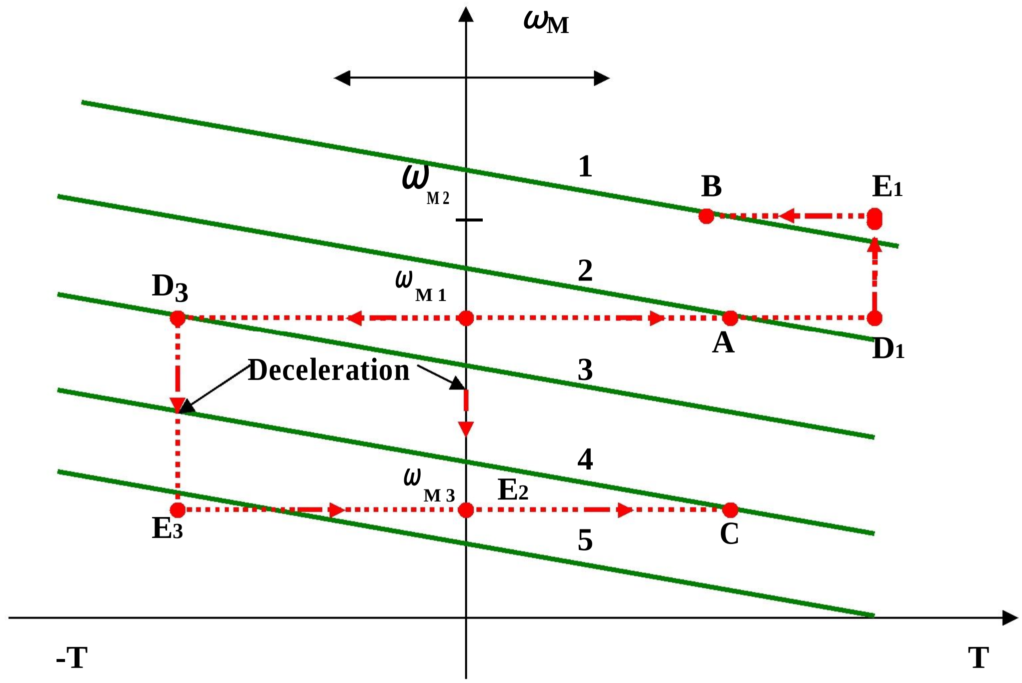
a direction to oppose the motion. The steady state operation is obtained at a speed for which braking torque equal the load torque. Drive operates in quadrant II or IV depending upon the rotation.



Acceleration and Deceleration modes are transient modes. Drive operates in acceleration mode whenever an increase in its speed is required. For this motor speed torque curve must be changed so that motor torque exceeds the load torque. Time taken for a given change in speed depends on inertia of motor load system and the amount by which motor torque exceeds the load torque.

Increase in motor torque is accompanied by an increase in motor current. Care must be taken to restrict the motor current with in a value which is safe for both motor and power modulator. In applications involving acceleration periods of long duration, current must not be allowed to exceed the rated value. When acceleration periods are of short duration a current higher than the rated value is allowed during acceleration. In closed loop drives requiring fast response, motor current may be intentionally forced to the maximum value in order to achieve high acceleration.

Figure shown below shows the transition from operating point A at speed ω_{m1} to operating point B at a higher speed ω_{m2} , when the motor torque is held constant during acceleration. The path consists of AD_1E_1B. In the figure below, 1 to 5 are motor speed torque curves. Starting is a special case of acceleration where a speed change from 0 to a desired speed takes place. All points mentioned in relation to acceleration are applicable to starting. The maximum current allowed should not only be safe for motor and power modulator but drop in source voltage caused due to it should also be in acceptable limits. In some applications the motor should accelerate smoothly, without any jerk. This is achieved when the starting torque can be increased step lessly from its zero value. Such a start is known as soft start.



Motor operation in deceleration mode is required when a decrease in its speed is required. According to the equation $T = T_l + J\frac{d\omega_m}{dt}$, deceleration occurs when load torque exceeds the motor torque. In those applications where load torque is always present with substantial magnitude, enough deceleration can be achieved by simply reducing the motor torque to zero. In those applications where load torque may not always have substantial amount or where simply reducing the motor torque to zero does not provide enough deceleration, mechanical brakes may be used to produce the required magnitude of deceleration. Alternatively, electric braking may be employed. Now both motor and the load torque oppose the motion, thus producing larger deceleration. During electric braking motor current tends to exceed the safe limit. Appropriate changes are made to ensure that the current is restricted within the safe limit.

Figure shown above shows paths followed during transition from point A at speed ω_{m1} to a point C at a lower speed ω_{m3} .When deceleration is carried out using electric braking at a constant braking torque, the operating point moves along the path AD_3E_3C. When sufficient load torque is present or when mechanical braking is used the operation takes place along the path AD_2E_2C. Stopping is a special case of deceleration where the speed of a running motor is changed to zero.

Problems:

A motor having a suitable control circuit develops a torque by the relationship $T_M = a\omega + b$, where a and b are positive constants. This motor is used to drive a load whose torque is expressed as $T_L = c\omega^2 + d$, where c and d are positive constants. The total inertia of the rotating masses is J.

a) **Determine the relations amongst the constants a, b, c and d in order that the motor can start together with the load and have an equilibrium operating speed?**

b) **Calculate the equilibrium operating speed?**

c) **Will the drive be stable at this speed?**

d) **Determine the initial acceleration of the drive?**

e) **Determine the maximum acceleration of the drive?**

Solution:

a) **At $\omega = 0$, T_M=b and T_L=d**

Hence the motor can start with the load only if b > d T_M=T_L at equilibrium speed

i.e. $a\omega + b = c\omega^2 + d$

i.e. $c\omega^2 - a\omega - (b - d) = 0$

Hence $\omega = \dfrac{a \pm \sqrt{a^2 + 4c(b-d)}}{2c}$

In order that ω is finite $a^2 + 4c(b-d) > 0$, which is true

+ Sign before the radical will give a positive ω as long as

$a^2 + 4c(b-d) > 0$

− sign before the radial will give a positive ω

only if $\dfrac{a}{2c} > \dfrac{\sqrt{a^2 + 4c(b-d)}}{2c}$

i.e. $a^2 > a^2 + 4c(b-d)$

i.e. $4c(b-d) < 0$

i.e c<0, which is not true, since c is given to be a positive constant. Hence the + sign before the radial only will give a positive finite equilibrium speed.

If $\sqrt{a^2 + 4c(b-d)} > 0$

b) **Equilibrium speed** $\omega = \dfrac{a + \sqrt{a^2 + 4c(b-d)}}{2c}$

c) $\frac{dT_L}{d\omega} = 2c\omega$ and $\frac{dT_M}{d\omega} = a$

If the equilibrium speed has to be stable

$\frac{dT_L}{d\omega} > \frac{dT_M}{d\omega}$ i.e. $2c\omega > a$

from the answer to (b), we have

$2c\omega = a + \sqrt{a^2 + 4c(b-d)}$ which will be always > a

Hence, the equilibrium operating speed determined earlier is a stable point of operation of drive.

d) Accelerating torque $J\frac{d\omega}{dt} = T_M - T_L$

Initially T_M=b and T_L=d

Therefore, initial acceleration = $\frac{b-d}{J}$

e) Accelerating torque $J\frac{d\omega}{dt} = T_M - T_L$

$$= a\omega - c\omega^2 + b - d$$

Therefore, acceleration A = $\frac{d\omega}{dt} = \frac{a\omega - c\omega^2 + b - d}{J}$

This will be maximum at a speed when

$$\frac{dA}{d\omega} = 0$$

$$\frac{a - 2c\omega}{J} = 0$$

$$\omega = \frac{a}{2c}$$

Substituting this speed at which the acceleration is maximum, in the general expression for acceleration, we get

$$A_{max} = \frac{(a^2/2c) - (a^2/4c) + b - d}{J}$$

$$= \frac{a^2 + 4c(b-d)}{4cJ}$$

MODULE II

DC MOTOR DRIVES – SINGLE PHASE & THREE PHASE RECTIFIER CONTROLLED DRIVES

DC Motor Drive Systems

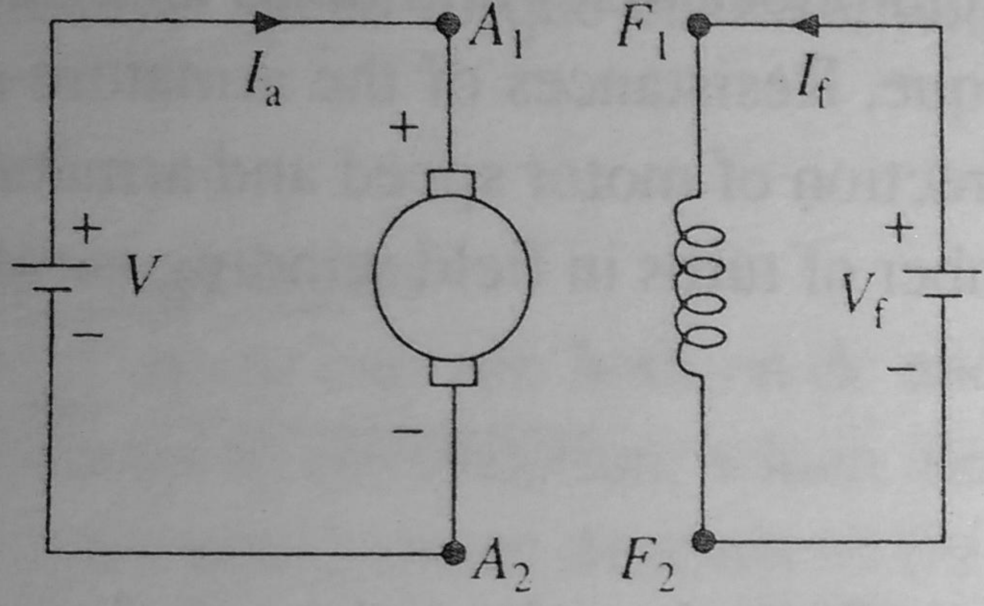
- DC motors are widely used in applications which require good speed control, speed regulation, frequent starting, braking & speed reversal etc
- E.g. for such applications are lifts, traction, cranes, hoists, machine tools, printing presses, textile mills etc.
- Low power DC motors are used for position control applications
- Commonly used DC motors are

  a. Separately excited DC motors

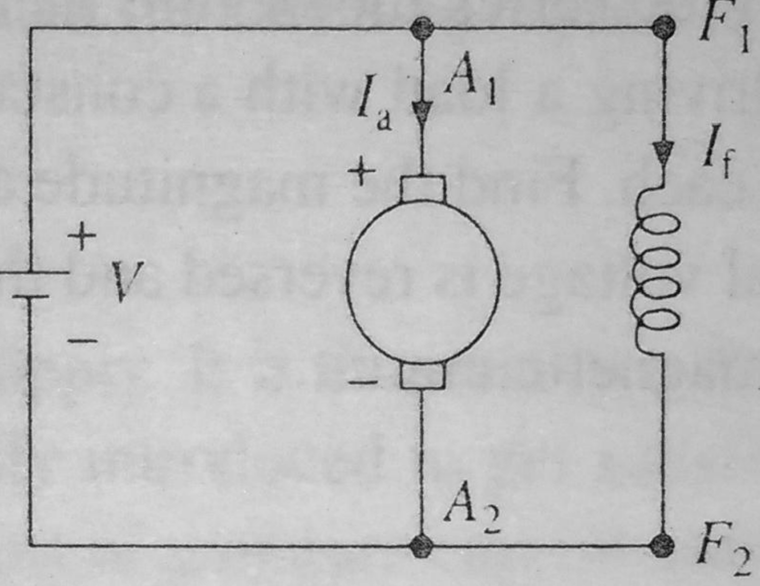
  b. Shunt motors

  c. Series motors

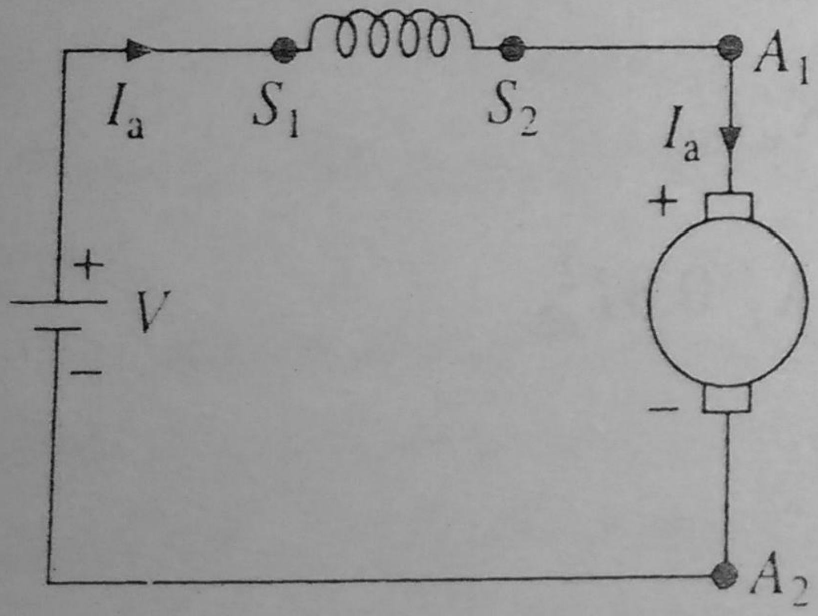
  d. Cumulatively Compound motors



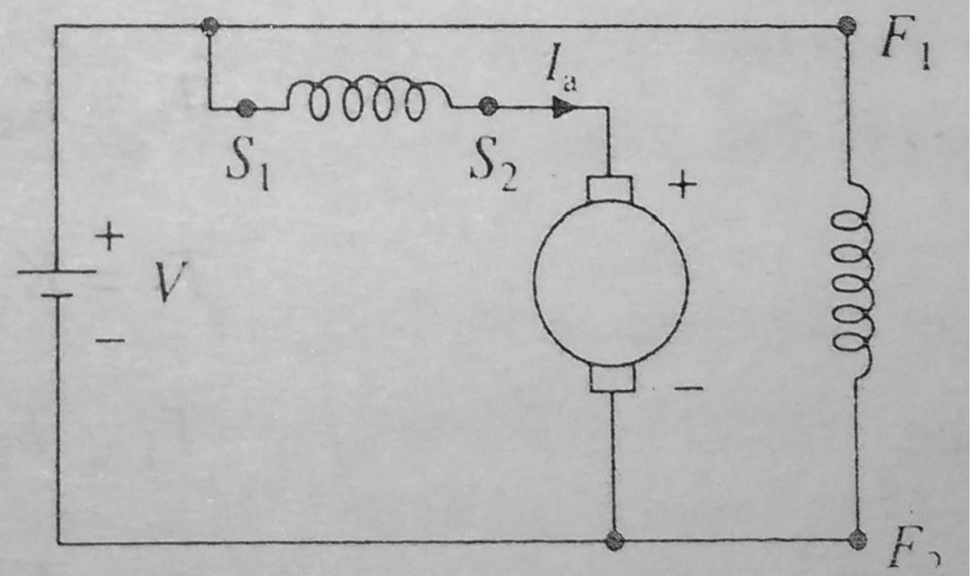
(a) Separately excited



(b) Shunt



(c) Series



(d) Cumulatively compound

- Basic equations applicable to all DC motors are

$V = E_b + I_a R_a$ .... (1)

$E_b = K_e \phi \omega_m$ .... (2)

$T = K_e \phi I_a$ .... (3)

where V = applied voltage, E_b = back emf, I_a = armature current, R_a = armature resistance, ϕ = flux/pole, ω_m = angular velocity, T = torque produced by motor, K_e = motor constant

From (1), $E_b = V - I_a R_a$ .... (4)

From (3), $I_a = T/(K_e \phi)$ .... (5)

Substituting (2) & (5) in (4)

=> $K_e \phi \omega_m = V - (T/(K_e \phi))R_a$

i.e, $\omega_m = \frac{V}{K_e \phi} - \frac{R_a}{(K_e \phi)^2} T$ .... (6)

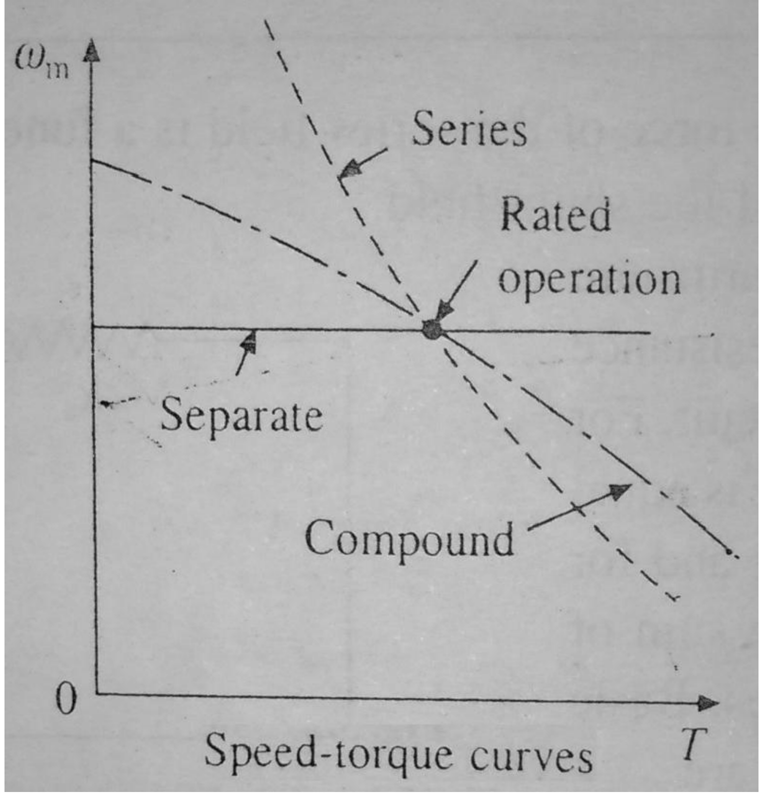
Shunt & separately excited motor

- Here field current is constant & flux can be assumed to be constant, i.e, $K_e\phi = K$, a constant

(2) => $E_b = K\omega_m$

(3) => $T = KI_a$

(6) => $\omega_m = (V/K) - (R_a/K^2)T$

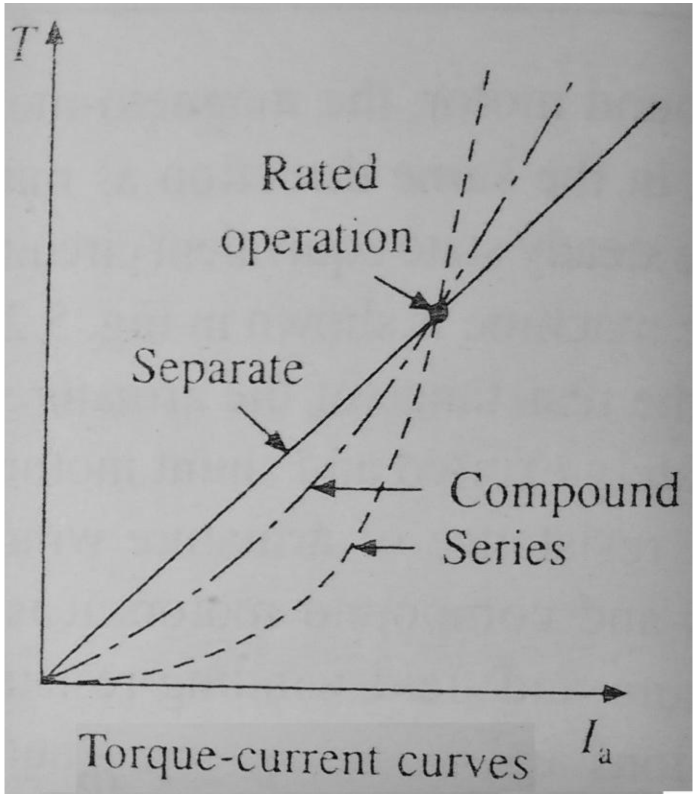


Series motor

- Here flux is a function of armature current i.e, $\phi \propto I_a$, $\phi = K_f I_a$

(3) => $T = K_e K_f I_a^2$

(6) => $\omega_m = (V/(K_e K_f I_a)) - (R_a/K_e K_f)$



Compound motor

- Here no load speed depends on strength of shunt field and slope of characteristics depends on strength of series field
- Cumulatively compound motors are used in those applications where drooping characteristics similar to series motor is required & at the same time no load speed limited to a safe value.

Speed control of DC motors

- According to the equation, $\omega_m = \dfrac{V}{K_e\phi} - \dfrac{R_a}{(K_e\phi)^2} T$

  Motor speed can be controlled by following methods,

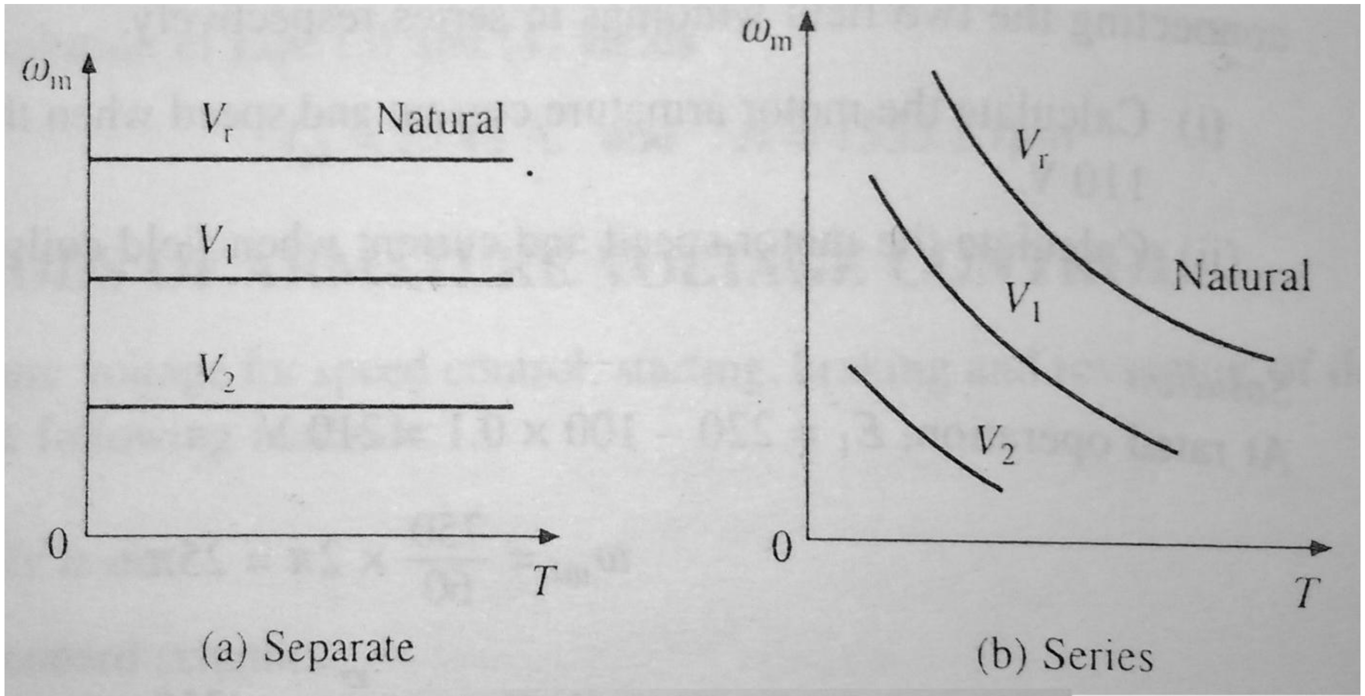
i) Armature voltage control

ii) Field flux control

iii) Armature resistance control

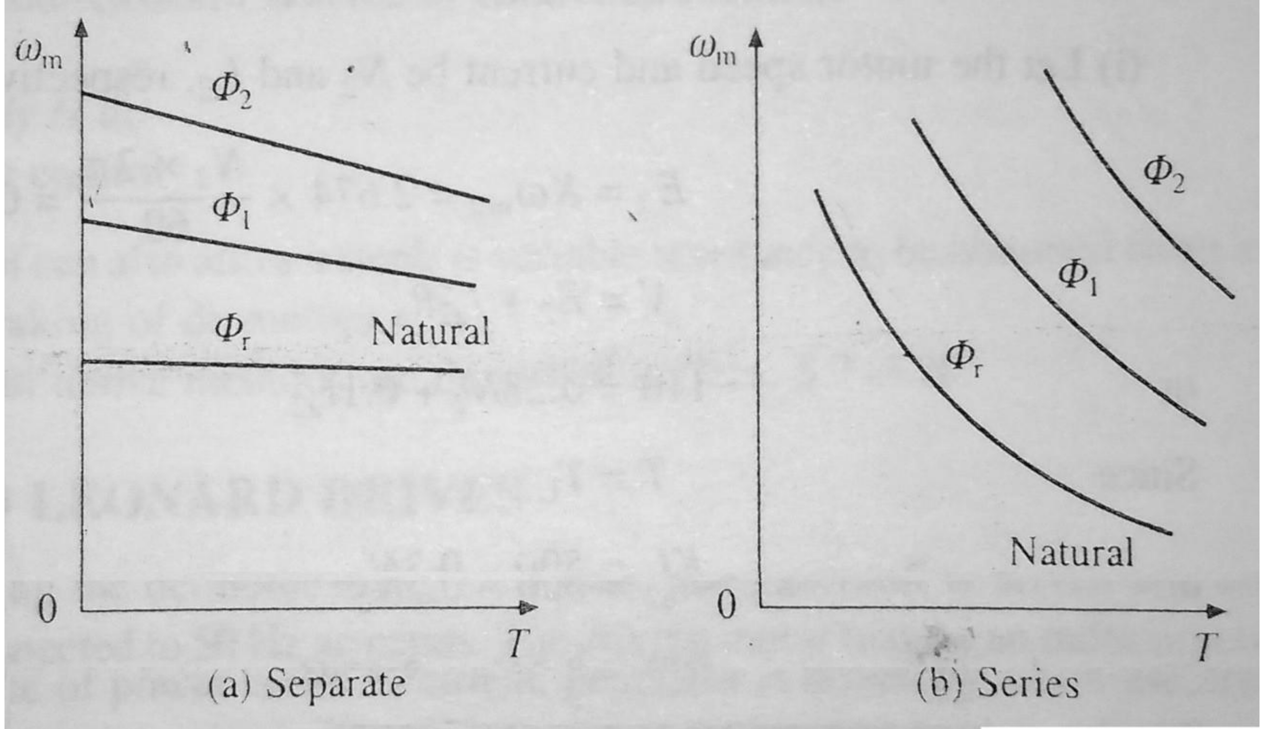
- Speed-torque curves of DC motors for these methods of speed control are shown below

i)



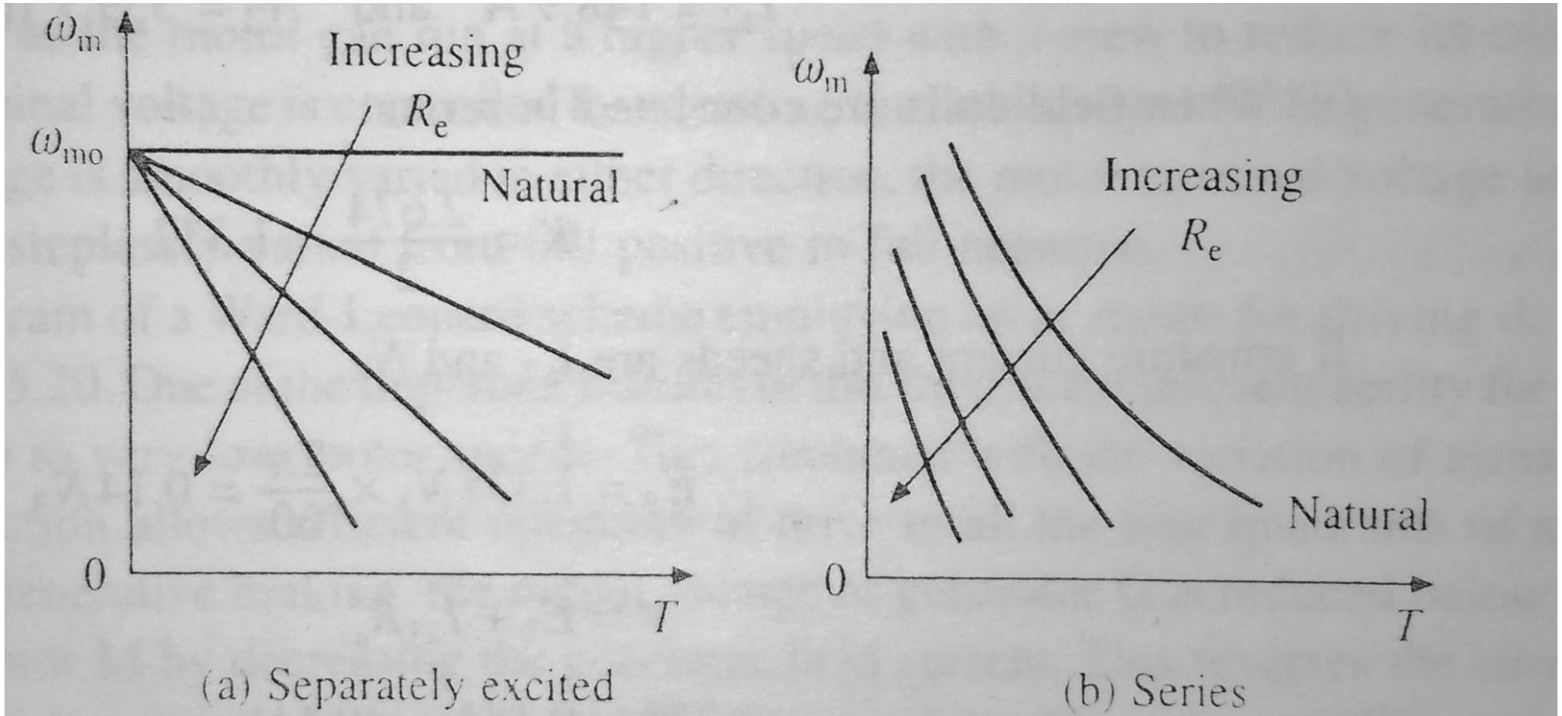
Armature voltage control V_r (rated) $> V_1 > V_2$

ii)



Field flux control Φ_r (rated) > Φ_1 > Φ_2

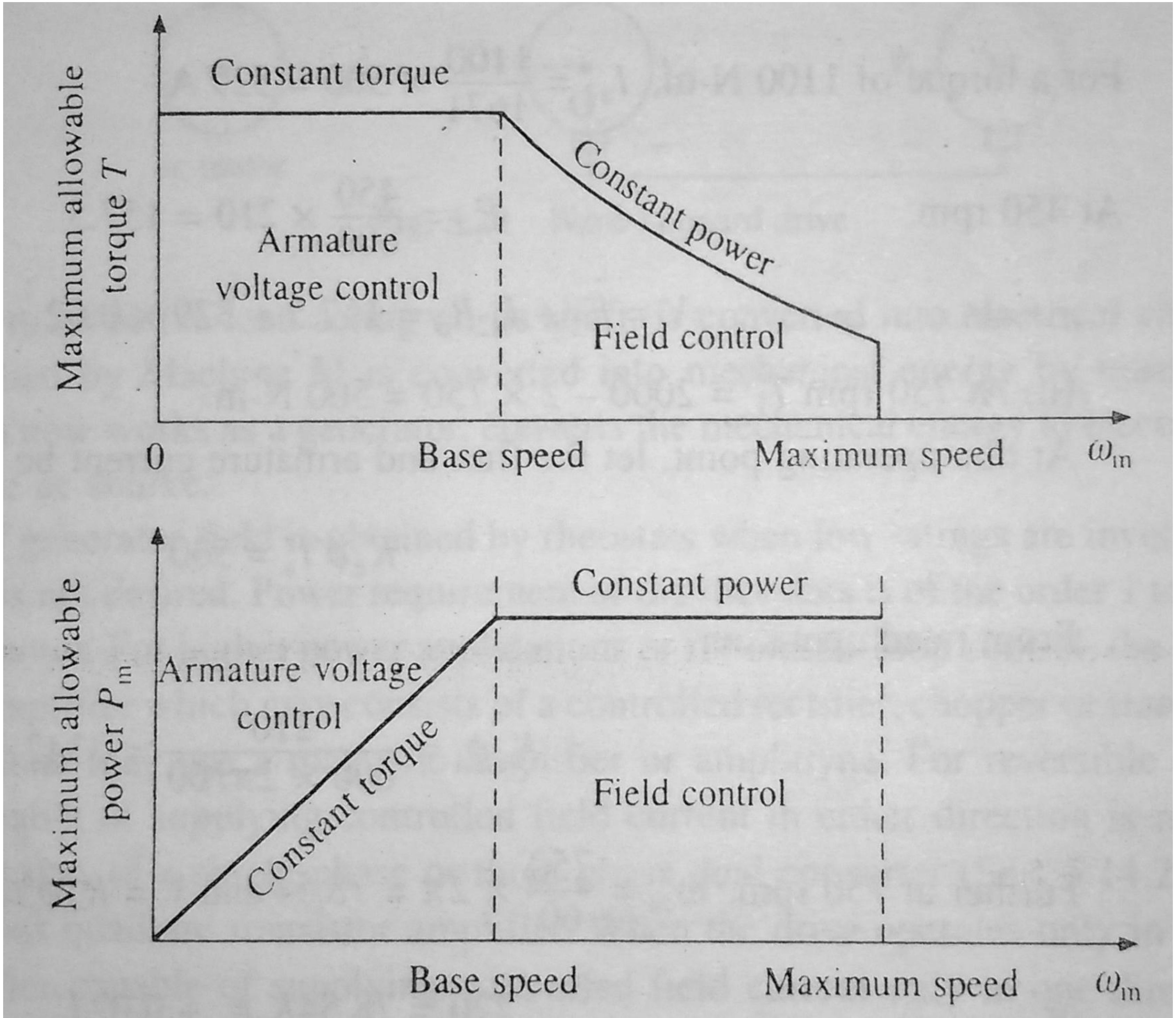
iii)



Speed torque curves of dc motors with resistance control. R_e: external resistance

- ***In armature voltage control***, the applied voltage across armature is varied to get the desired speed control
- But *it can provide speed control only below rated speed* because armature voltage cannot be increased above rated value
- For *speed control above rated speed*, ***field flux control*** is employed
- In a separately excited DC motor, flux is controlled by varying voltage across field winding & in a series motor it is controlled either by varying number of turns in field winding or connecting a diverter resistance across field winding
- In ***armature resistance control***, speed is controlled by wasting power in external resistors that are connected in series with armature

The **maximum Torque & Power limitations of DC drives** is shown below.



Variation of Torque

- We know $T \propto \phi I_a$. During armature voltage control, flux in the machine is kept constant.
- i.e, $T \propto I_a$. Also I_a is limited to maximum rated current.
- So during this period, maximum torque that can be produced by a motor remains constant.
- For speed above rated speed, we have to go for flux control.
- Here as flux (ϕ) changes, speed increases & T decreases

Variation of Power

- Power, P =VI. During armature voltage control, as 'V' varies, power also varies.
- During flux control (speed above rated speed), 'V' is maintained constant at rated value.
- So power $\propto$ current(I). Since maximum value of current is limited to rated value, the maximum power that can be produced by the motor Remains constant.

Methods of armature voltage control

When supply is AC, we can go for

i) Ward-Leonard scheme

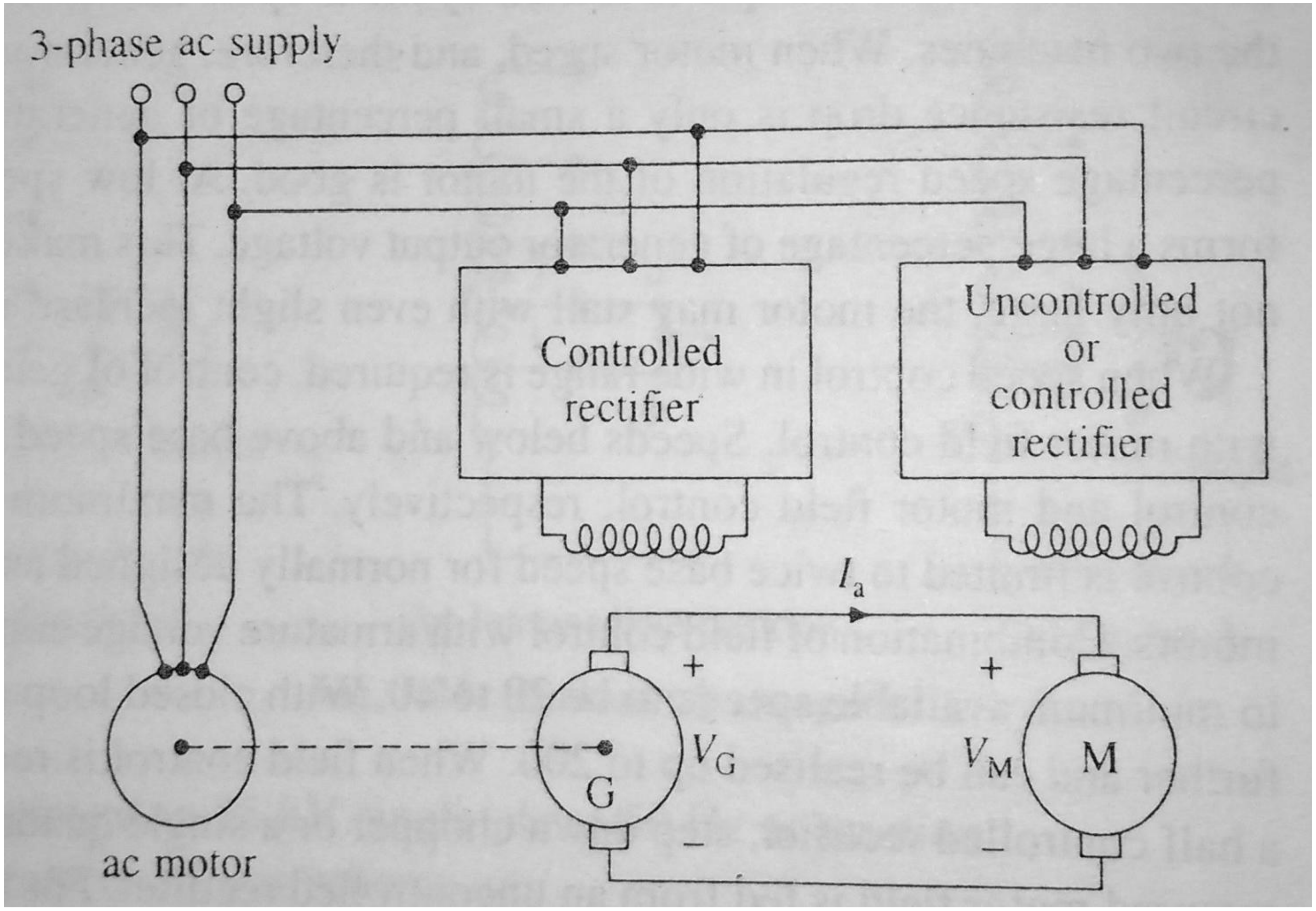
ii) Transformer with taps & uncontrolled rectifier

iii) Controlled rectifier

When supply is DC,

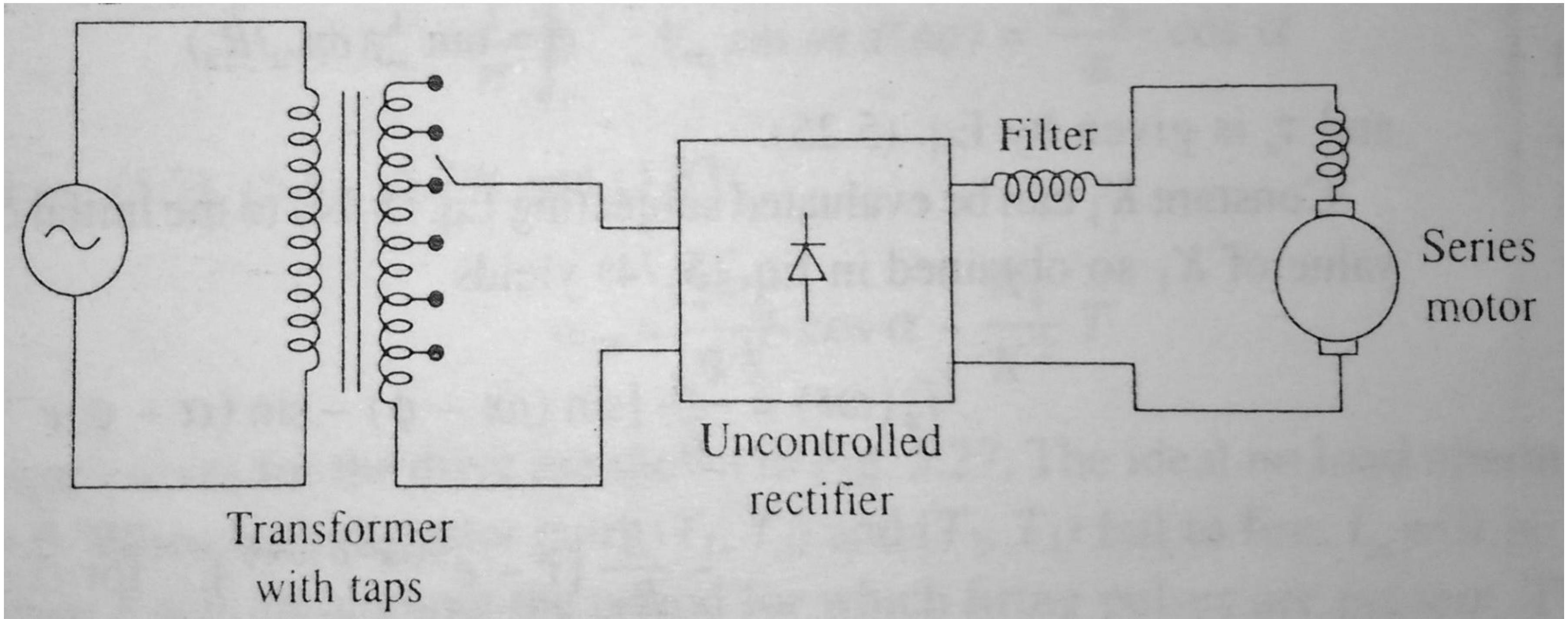
iv) Chopper control

i) Ward-Leonard scheme



- Here the speed of DC motor is controlled by armature voltage control
- The armature voltage is supplied by the separately excited DC generator. So by controlling generated emf of generator, we can control the speed of motor
- The generated emf can be controlled by varying the flux in the machine
- Due to high initial cost, maintenance & low efficiency, this system is not using currently

ii) <u>Transformer & uncontrolled rectifier</u>



- Variable voltage for DC motor control can be obtained by either using an autotransformer or a transformer with tapings followed by an uncontrolled rectifier
- Autotransformer is used for low power applications & for high power applications a transformer with tapings is employed
- Here to control the speed of the motor, the input AC voltage to uncontrolled rectifier is varied

iii) Controlled rectifier

- Controlled rectifiers are used to get variable DC voltage from an AC source of fixed voltage (Also known as static Ward-Leonard drives)
- Commonly used controlled rectifier circuits are,

i) 1 ϕ Half wave controlled rectifier

ii) 1 ϕ fully controlled rectifier

iii) 1 ϕ half controlled rectifier

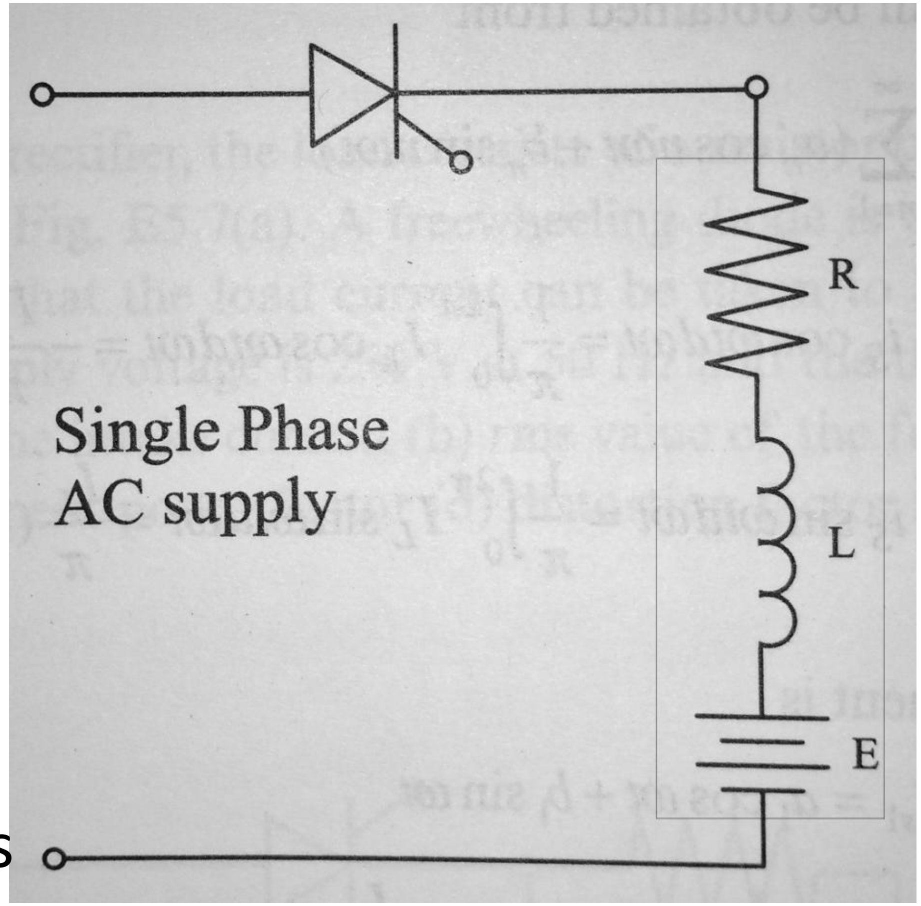
iv) 3 ϕ fully controlled rectifier

v) 3 ϕ half controlled rectifier

iv) Chopper

- Used to get a variable DC voltage from a fixed voltage DC source

Single phase half wave controlled rectifier fed separately excited DC motor drive



- The drive circuit is shown in figure
- Motor is shown by its equivalent circuit
- Field supply is not shown. When field control is required, field is fed from a controlled rectifier.
- The AC input voltage is defined by,

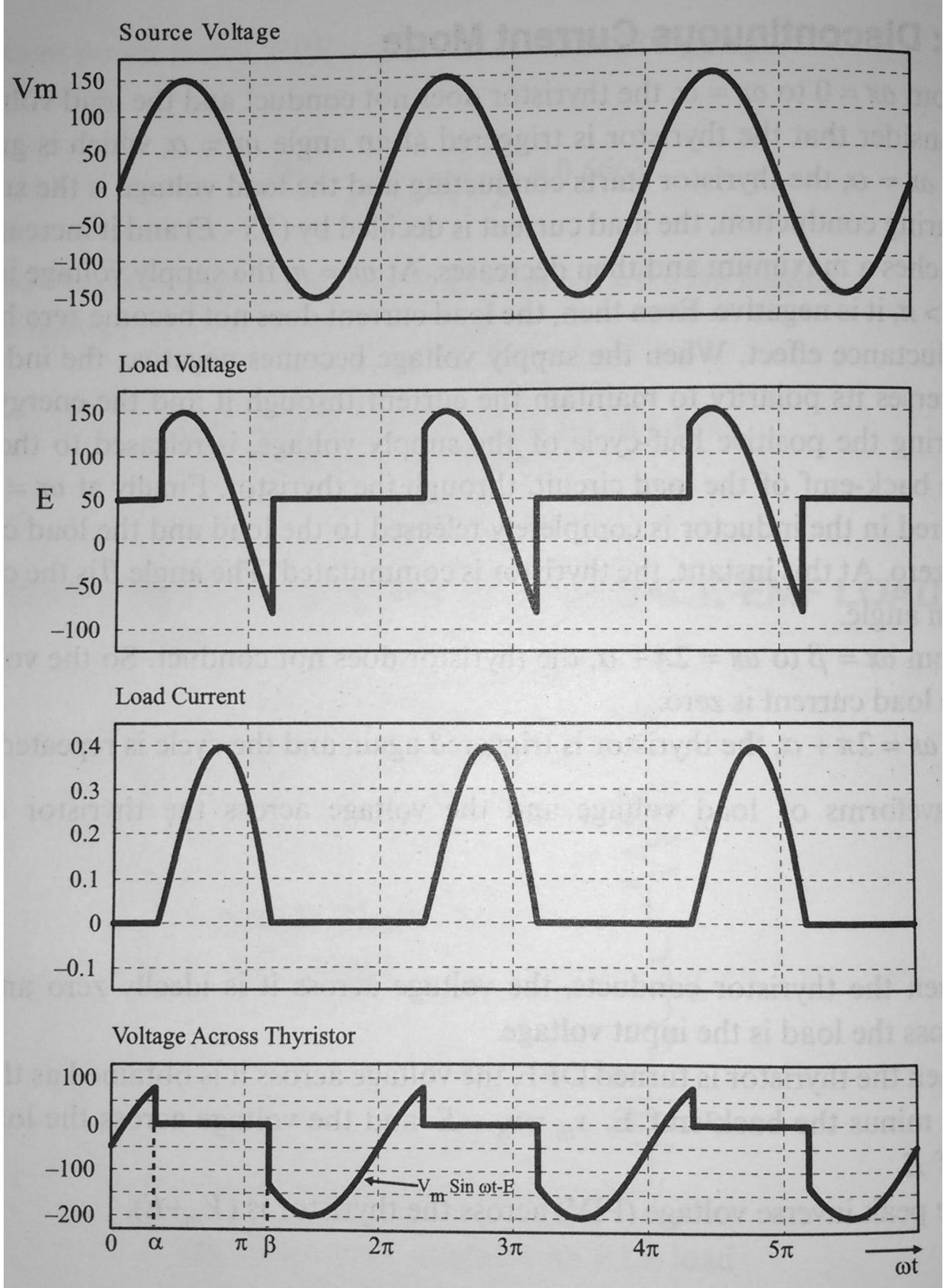
  $V_s = V_m \sin\omega t$
- Here the thyristor can be triggered only when it is forward biased. This happens when supply voltage is greater than back emf, E

- If ‘θ’ is the minimum firing angle below which thyristor cannot be turned on, then $V_m \sin\omega t = E$ or $\theta = \sin^{-1}(E/V_m)$
- The maximum value of firing angle ‘θ’ = $(\pi - \theta)$

<u>Working</u>

- From $\omega t = 0$ to $\omega t = \alpha$, thyristor does not conduct & load voltage, $V_0 = E$
- Consider that the thyristor is triggered at an angle $\omega t = \alpha$, which is greater than ‘θ’
- At $\omega t = \alpha$, thyristor starts conduction & load voltage = V_s
- During conduction, load current is decided by $(V_s - E)$ & it increases from zero, reaches a maximum value & decreases
- At $\omega t = \pi$, supply voltage = 0 & for $\omega t > \pi$, it is negative
- Even then load current does not become zero because of inductive effect
- When supply voltage become negative, inductor quickly reverses its polarity to maintain the current through it & energy stored in it during positive half cycle is released to resistor & back emf of motor Through thyristor.

- Finally at $\omega t = \beta$, energy stored in the inductor is completely released to load & load current decays to zero. Now thyristor is commutated.
- β is called extinction angle
- From $\omega t = \beta$ to $\omega t = 2\pi + \alpha$, thyristor does not conduct. So load voltage is E & current = 0
- At $\omega t = 2\pi + \alpha$, thyristor is triggered again & the cycle is repeated



Average value of output voltage (Voltage applied to armature),

$$V_{avg} = \frac{1}{2\pi}\left[\int_{\alpha}^{\beta} V_m Sin\omega t + \int_{\beta}^{2\pi+\alpha} E d\omega t\right] = \frac{1}{2\pi}\left[V_m \quad -Cos\,\omega t\right]_{\alpha}^{\beta} + E \quad \omega t\Big]_{\beta}^{2\pi+\alpha}\Big]$$

β

$$V_{avg} = \frac{1}{2\pi}\left[V_m(Cos\alpha - Cos\beta) + E(2\pi + \alpha - \beta)\right]$$

- Average value of load current = (Average value of voltage across resistor/ Resistance value (R))
- When the thyristor conducts, on applying KVL we can form an equation,

  V_m Sinωt = L(di/dt) + iR + E

  Voltage across resistor, iR = V_mSinωt - L(di/dt) – E

  Average value of voltage across resistor = $\frac{1}{2\pi}\int_{0}^{2\pi} iR\,dt$

- i.e, Average load current, $I_{avg} = \frac{V_{res_{avg}}}{R} = \frac{1}{2\pi R}\int_0^{2\pi}[V_m Sin\omega t - E]d\omega t$

(average value of voltage across inductor = 0, so the term L(di/dt) can be neglected)

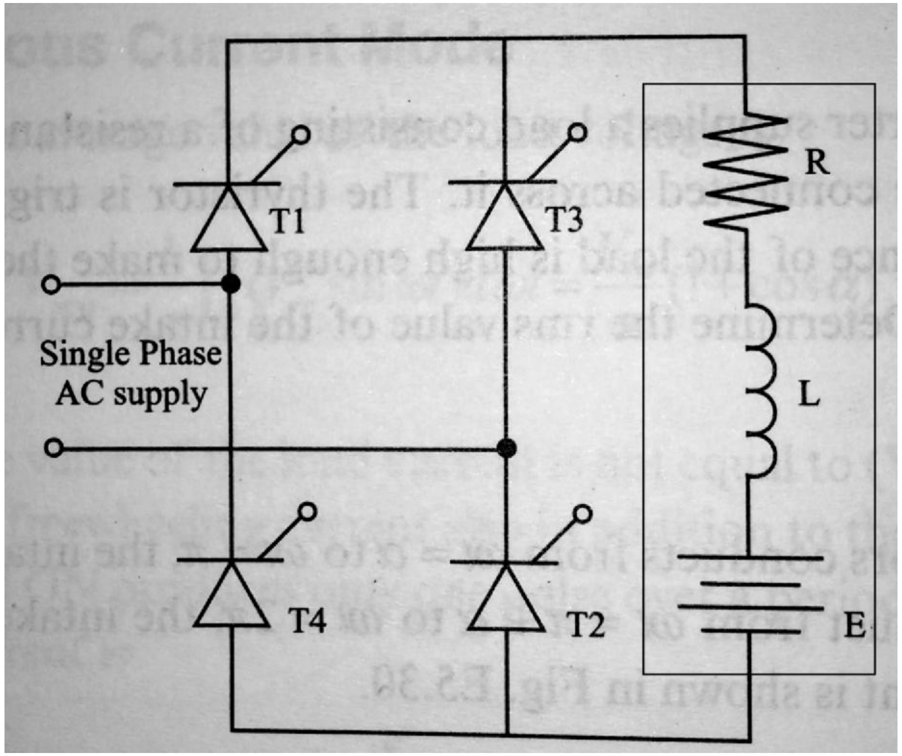
$$= \frac{1}{2\pi R}\int_\alpha^\beta (V_m Sin\omega t - E)d\omega t$$

$$= \frac{1}{2\pi R}\left[V_m\,(-Cos\,\omega t)\right]_\alpha^\beta - E\,(\omega t)\Big]_\alpha^\beta\Big]$$

$$I_{avg} = \frac{1}{2\pi R}[V_m(Cos\,\alpha - Cos\,\beta) - E(\beta - \alpha)]$$

- From (7) it is clear that by varying firing angle 'α', DC output voltage of rectifier can be varied and by applying this variable DC voltage to armature we can control the speed of the motor according to (6)
- This is a single quadrant drive (1^{st} quadrant – forward motoring , Since the average value of output voltage is always positive)

Single phase fully controlled bridge rectifier fed separately excited DC motor drive



- The drive circuit is shown in figure
- Motor is shown by its equivalent circuit
- Field supply is not shown. When field control is required, field is fed from a controlled rectifier.
- The AC input voltage is defined by,

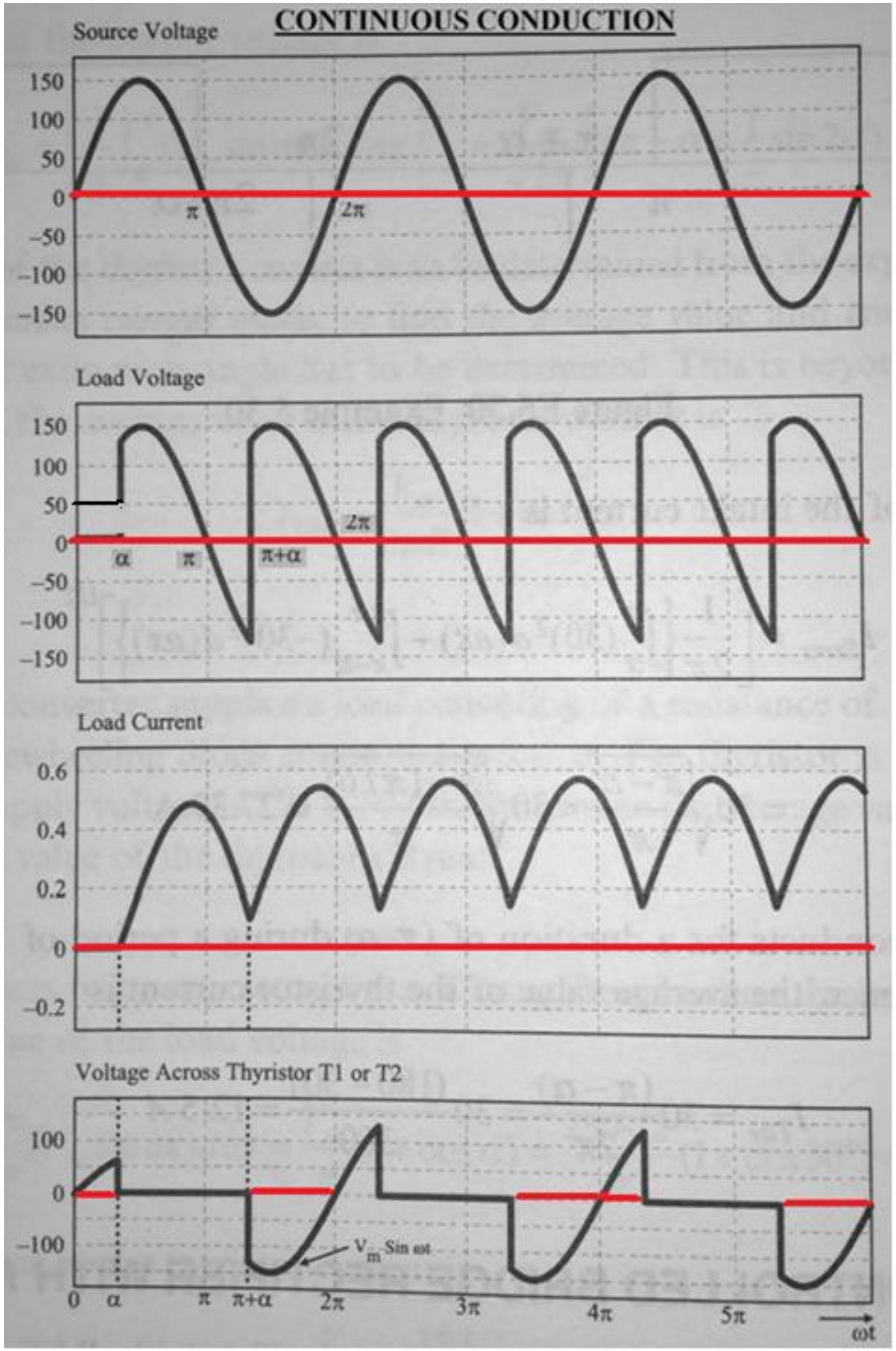
  $V_s = V_m \sin\omega t$
- Here the motor current can be continuous or discontinuous
- If 'θ' is the minimum firing angle below which thyristor cannot be turned on, then $V_m \sin\omega t = E$ or $\theta = \sin^{-1}(E/V_m)$

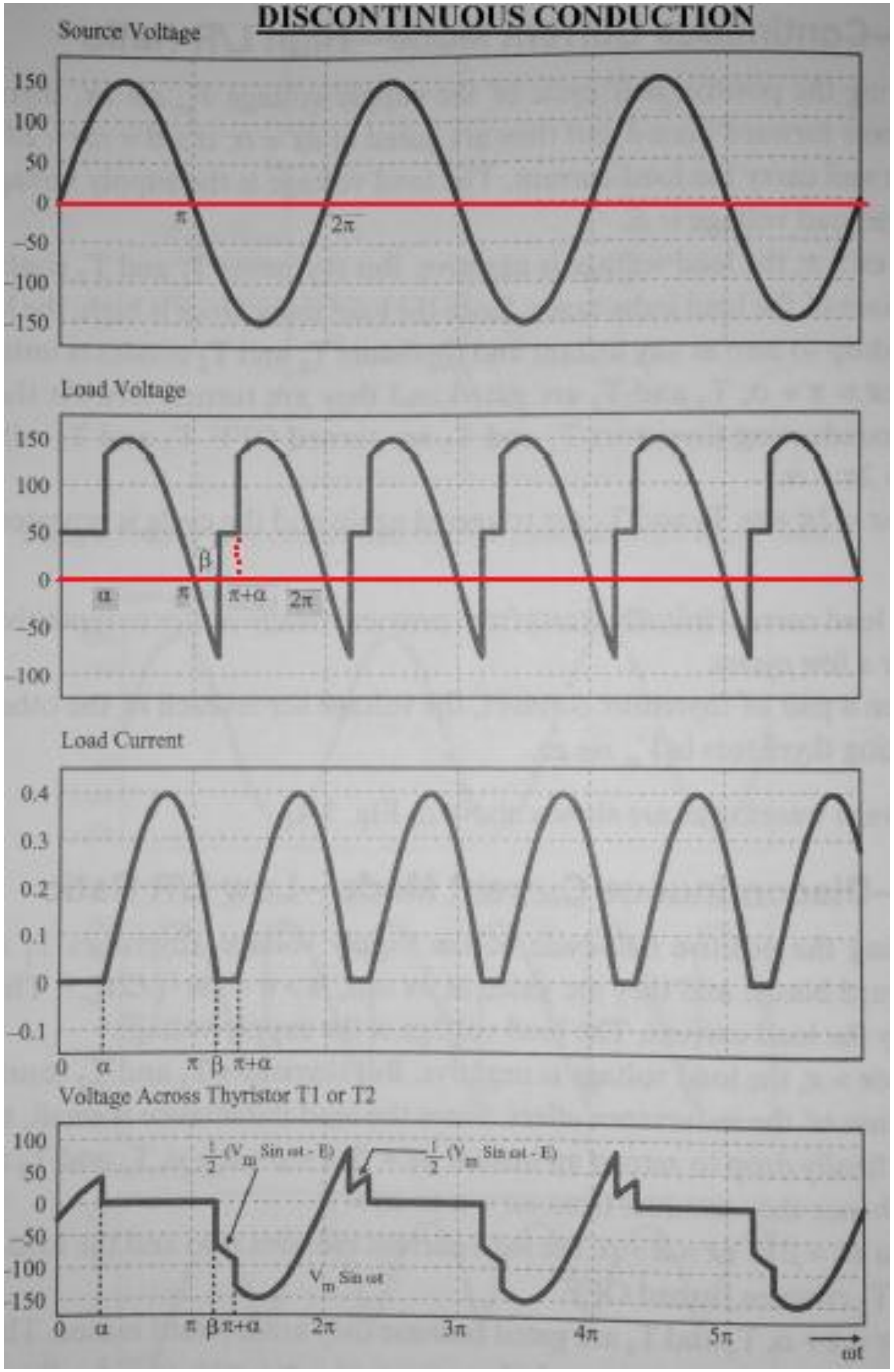
__Working – Continuous current mode__ (high L/R ratio)

- During positive half cycle of supply voltage, thyristors T_1 & T_2 become forward biased and they are gated at $\omega t=\alpha$. They conduct & carry the load current. The load voltage is the supply voltage.
- From $0 < \omega t < \alpha$, the load voltage is E
- For $\omega t > \pi$, load voltage is negative. But thyristors T_1 & T_2 continue to conduct because of load inductance. T_1 & T_2 conduct until $\omega t = \pi+\alpha$
- At $\omega t = \pi+\alpha$, T_3 & T_4 are gated & they are turned ON. At the same instant T_1 & T_2 turned OFF. T_3 & T_4 conducts until $\omega t = 2\pi+\alpha$
- At $\omega t = 2\pi+\alpha$, T_1 & T_2 are triggered again & the cycle is repeated

__Working – Discontinuous current mode__ (low L/R ratio)

- During positive half cycle of supply voltage, thyristors T_1 & T_2 become forward biased and they are gated at $\omega t=\alpha$. They conduct & carry the load current. The load voltage is the supply voltage.
- From $0 < \omega t < \alpha$, the load voltage is E
- For $\omega t > \alpha$, load voltage is negative. But thyristors T_1 & T_2 continue to conduct because of load inductance until $\omega t = \beta$. T_1 & T2 are turned OFF at β


CONTINUOUS CONDUCTION
Source Voltage
Load Voltage
Load Current
Voltage Across Thyristor T1 or T2
α
π
π+α
2π
3π
4π
5π
V_m Sin ωt
ωt


DISCONTINUOUS CONDUCTION
Source Voltage
Load Voltage
Load Current
Voltage Across Thyristor T1 or T2
α
π
β
π+α
2π
3π
4π
5π
$\frac{1}{2}$(V_m Sin ωt - E)
$\frac{1}{2}$(V_m Sin ωt - E)
V_m Sin ωt
ωt

From $\omega t=\beta$ to $\omega t=\pi+\alpha$, the load current remains zero & load voltage is E.

- At $\omega t=\pi+\alpha$, T_3 & T_4 are gated. They conduct & load current flows through them from $\omega t=\pi+\alpha$ to $\omega t=\pi+\beta$
- At $\omega t=\pi+\beta$, load current is zero & hence T_3 & T_4 are turned OFF. During $\omega t=\pi+\beta$ to $\omega t=2\pi+\alpha$ no device conducts & load current is 0. Load voltage = E
- At $\omega t=2\pi+\alpha$, T_1 & T_2 are turned ON & the cycle is repeated

<u>For continuous current mode,</u>

Average value of output voltage (Voltage across armature),

$$V_{av} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m Sin\omega t\, d\omega t = \frac{V_m}{\pi}\left[-Cos\,\omega t\right]_{\alpha}^{\pi+\alpha}$$

$$V_{av} = \frac{2V_m}{\pi}Cos\,\alpha \qquad ....(9)$$

$\pi+\alpha$

- For 0<α<90, V_{av} is positive & it act as a rectifier. For 90<α<180, V_{av} is negative & it act as a linecommutated inveter

- Average value of load current = average value of voltage across the resistor/Resistance value

- When the thyristor conducts, on applying KVL we can form an equation, $V_m \, Sin\omega t = L(di/dt) + iR + E$

Voltage across resistor, $iR = V_m Sin\omega t - L(di/dt) - E$

Average value of voltage across resistor = $\frac{1}{\pi}\int_0^{\pi} iR\,dt$

i.e, Average load current, $I_{avg} = \frac{V_{res_{avg}}}{R} = \frac{1}{\pi R}\int_0^{\pi}(V_m Sin\,\omega t - E)\,d\omega t$

(average value of voltage across inductor = 0, so the term L(di/dt) can be neglected)

$$I_{avg} = \frac{1}{\pi R}\int_{\alpha}^{\pi+\alpha}(V_m Sin\,\omega t - E)\,d\omega t = \frac{1}{\pi R}\left[V_m\left(-Cos\,\omega t\right)\Big]_{\alpha}^{\pi+\alpha} - E\left(\omega t\right)_{\alpha}^{\pi+\alpha}\right]$$

$$i.e, \quad I_{avg} = \frac{2V_m}{\pi R}Cos\alpha - \frac{E}{R} = \frac{V_{avg} - E}{R}$$

Discontinuous current mode

From $\omega t=\alpha$ to $\omega t=\beta$, the load voltage is $V_m Sin\omega t$ and from $\omega t=\beta$ to $\omega t=\alpha+\pi$, the load voltage is E.

So average value of output voltage (Voltage across the armature),

$$V_{avg}=\frac{1}{\pi}\left[\int_{\alpha}^{\beta}(V_m Sin\omega t)d\omega t+\int_{\beta}^{\pi+\alpha}E d\omega t\right]$$

$$V_{avg}=\frac{1}{\pi}\left[V_m(Cos\alpha-Cos\beta)+E(\pi+\alpha-\beta)\right] \qquad ....(11)$$

Average value of load current,

$$I_{avg}=\frac{1}{\pi R}\int_{\alpha}^{\beta}(V_m Sin\omega t-E)d\omega t$$

$$i.e,\quad I_{avg}=\frac{1}{\pi R}\left[V_m(Cos\alpha-Cos\beta)-E(\beta-\alpha)\right] \qquad ....(12)$$

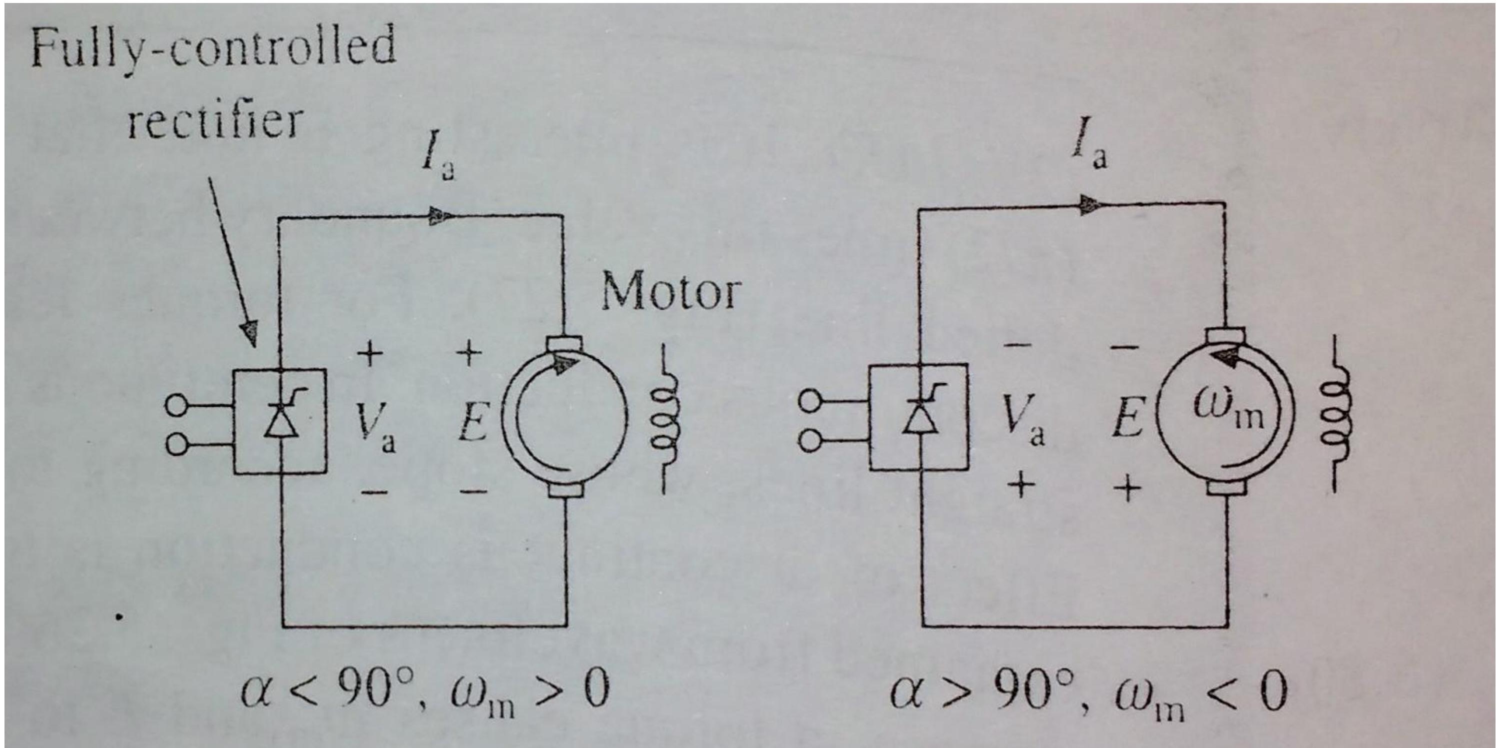
This drive can operate in 2 quadrants

1. *Quadrant I operation* (forward motoring)

   for ($0<\alpha<90$), the average output voltage of rectifier is positive & $V_a>E$. Now the machine will work as a motor

2. *Quadrant IV operation* (reverse braking)

   for ($90<\alpha<180$), the average output voltage of rectifier is negative & $V_a<E$. Now the motor will work in regenerative braking mode by supplying energy to source & rectifier will work as an inverter



(b) Motoring

(c) Regenerative braking

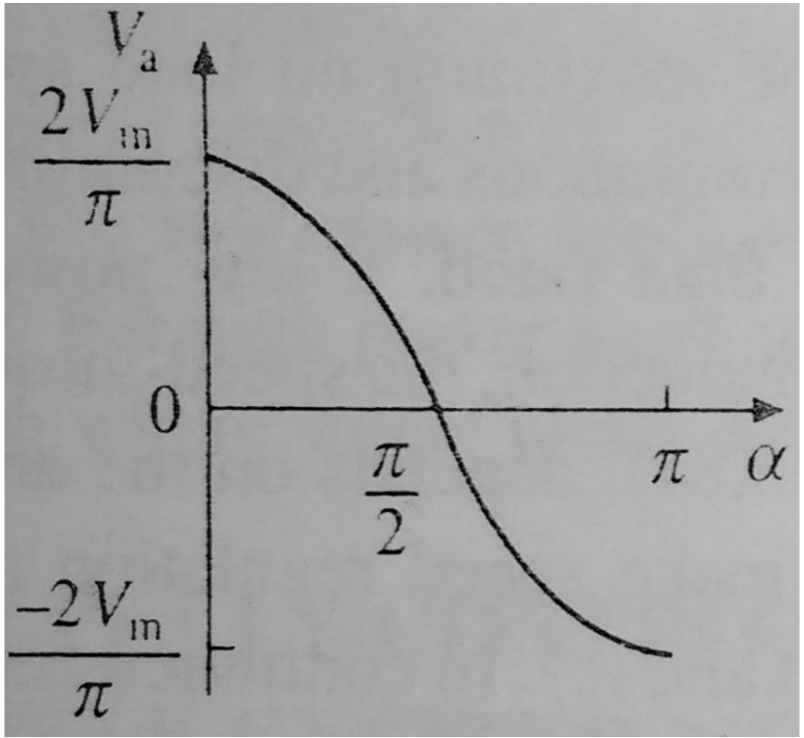
- for regenerative braking operation, α should be adjusted so that V_a is negative & E should be reversed by any of following method

  i) The load coupled to motor should drive the motor in reverse direction

  ii) Field current may be reversed with motor running in forward direction

  iii) Armature terminal connections may be reversed while motor running in forward direction

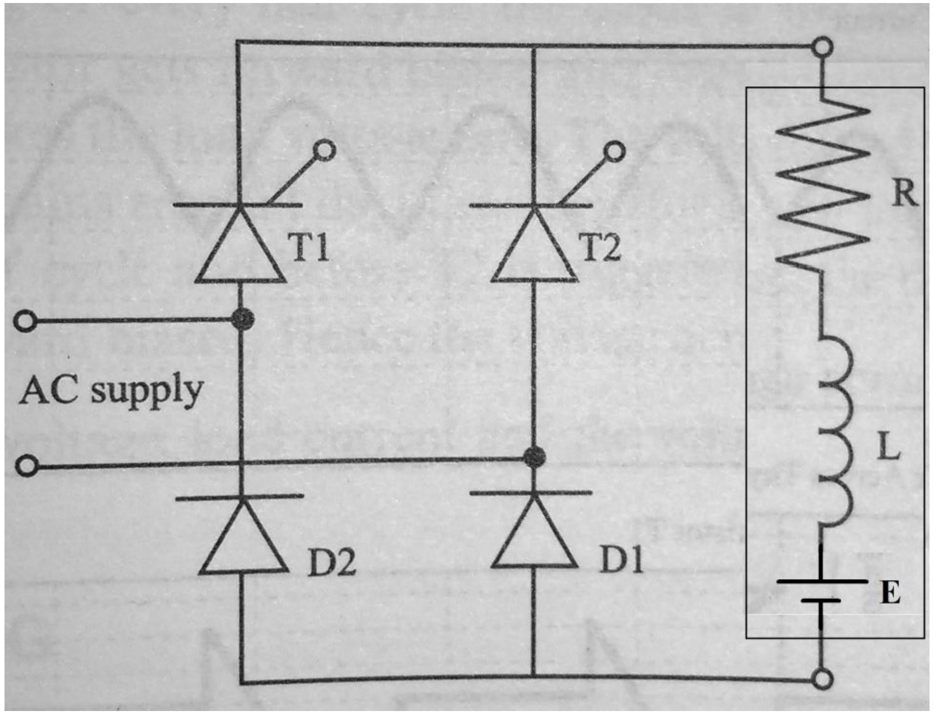
- The variation of motor input voltage as a function of α is shown below



Single phase half controlled bridge rectifier fed separately excited DC motor drive

- The drive circuit is shown in figure
- Motor is shown by its equivalent circuit
- Field supply is not shown. When field control is required, field is fed from a controlled rectifier.
- The AC input voltage is defined by,

  $V_s = V_m \text{Sin}\omega t$



- Here the motor current can be continuous or discontinuous
- If 'θ' is the minimum firing angle below which thyristor cannot be turned on, then $V_m \text{Sin}\omega t = E$ or $\theta = \text{Sin}^{-1}(E/V_m)$

Working – Continuous current mode (high L/R ratio)

- During positive half cycle of supply voltage, Thyristor T_1 & Diode D_1 are forward biased and T_1 is gated at $\omega t=\alpha$. They conduct & carry the load current. The load voltage is the supply voltage.
- For $\omega t > \pi$, load voltage is negative. But Thyristor T_1 continue to conduct because of load inductance. When supply voltage reverses, D_1 become reverse biased and turned off. At the same time D_2 become forward biased, starts conduction. So T_1 & D_2 conduct until $\omega t = \pi+\alpha$
- At $\omega t = \pi+\alpha$, T_2 is gated & turned ON. At the same instant T_1 gets turned OFF. T_2 & D_2 conducts until $\omega t = 2\pi$
- For $\omega t > 2\pi$, load voltage is positive. But Thyristor T_2 continue to conduct because of load inductance. When supply voltage reverses, D_2 become reverse biased and turned off. At the same time D_1 become forward biased, starts conduction. So T_2 & D_1 conduct until $\omega t = 2\pi+\alpha$
- At $\omega t = 2\pi+\alpha$, T_1 is triggered again & the cycle is repeated.

<u>Working – Discontinuous current mode</u> (low L/R ratio)

- During positive half cycle of supply voltage, Thyristor T_1 & Diode D_1 are forward biased and T_1 is gated at $\omega t=\alpha$. They conduct & carry the load current. The load voltage is the supply voltage.
- For $\omega t > \pi$, load voltage is negative. But Thyristor T_1 continue to conduct because of load inductance. When supply voltage reverses, D_1 become reverse biased and turned off. At the same time D_2 become forward biased, starts conduction. So T_1 & D_2 conduct until $\omega t = \beta$
- At $\omega t = \beta$, load current become zero. So T1 & D2 gets turned OFF
- From $\omega t = \beta$ to $\omega t = \pi+\alpha$, no devices conduct & load voltage = E
- At $\omega t = \pi+\alpha$, T_2 is gated & turned ON. T_2 & D_2 conducts until $\omega t = 2\pi$
- For $\omega t > 2\pi$, load voltage is positive. But Thyristor T_2 continue to conduct because of load inductance. When supply voltage reverses, D_2 become reverse biased and turned off. At the same time D_1 become forward biased, starts conduction. So T_2 & D_1 conduct until $\omega t = \pi+\beta$
- At $\omega t = 2\pi+\alpha$, T_1 is triggered again & the cycle is repeated.

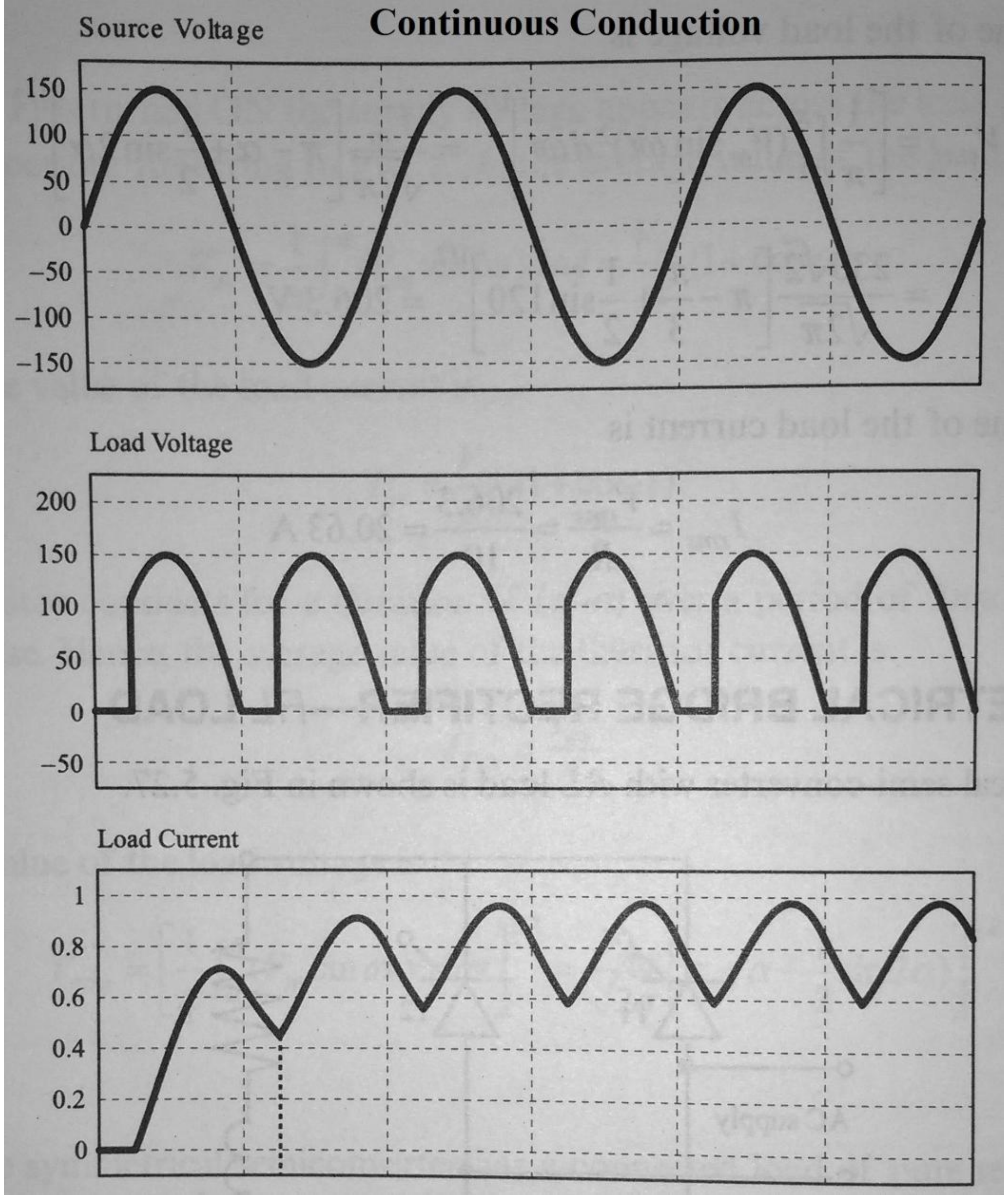
***For continuous current mode*,**

Average value of output voltage

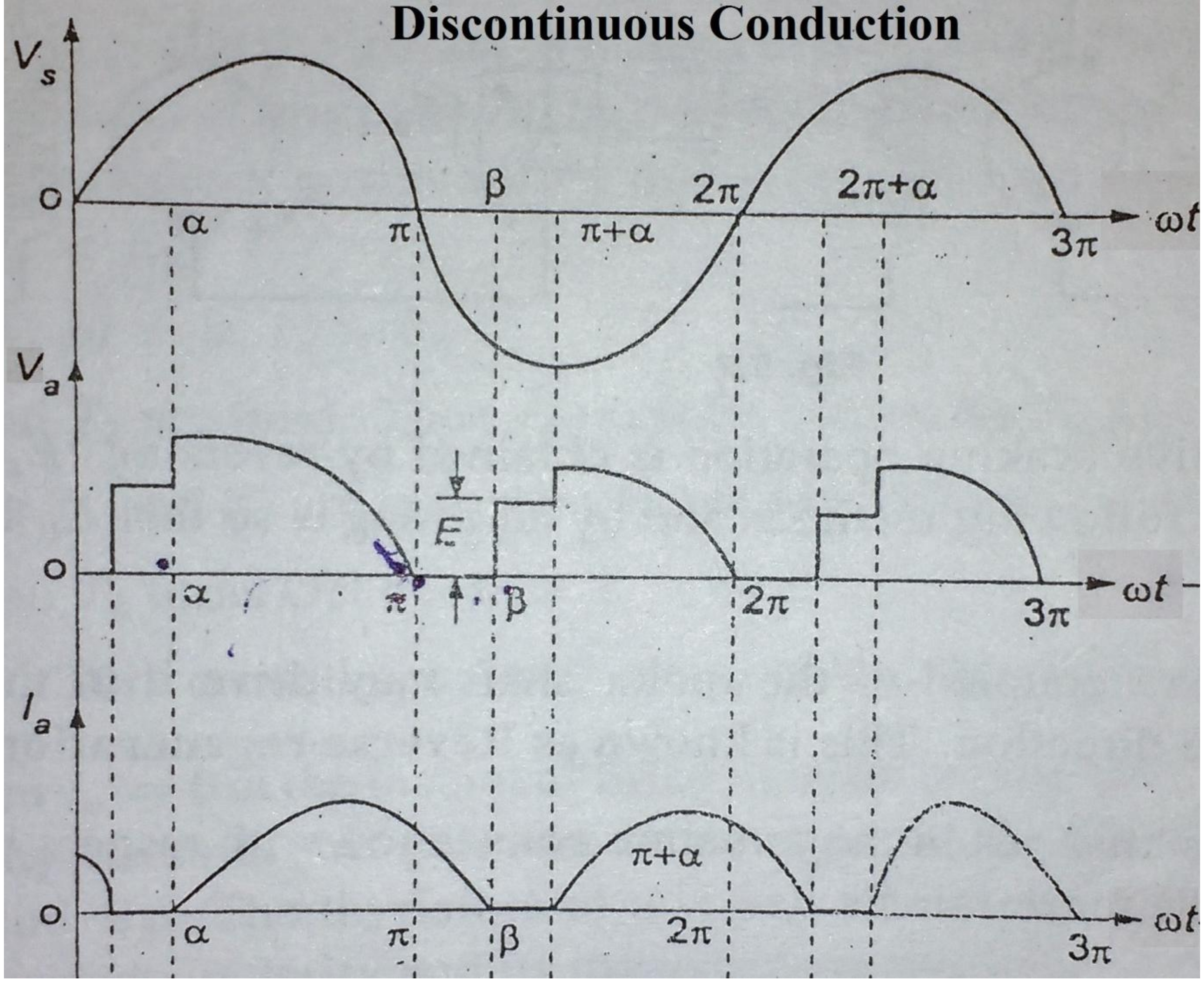
(Voltage across armature),

$$V_{avg} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m Sin\omega t\, d\omega t$$

$$i.e, \quad V_{avg} = \frac{V_m}{\pi}(1 + Cos\alpha)$$



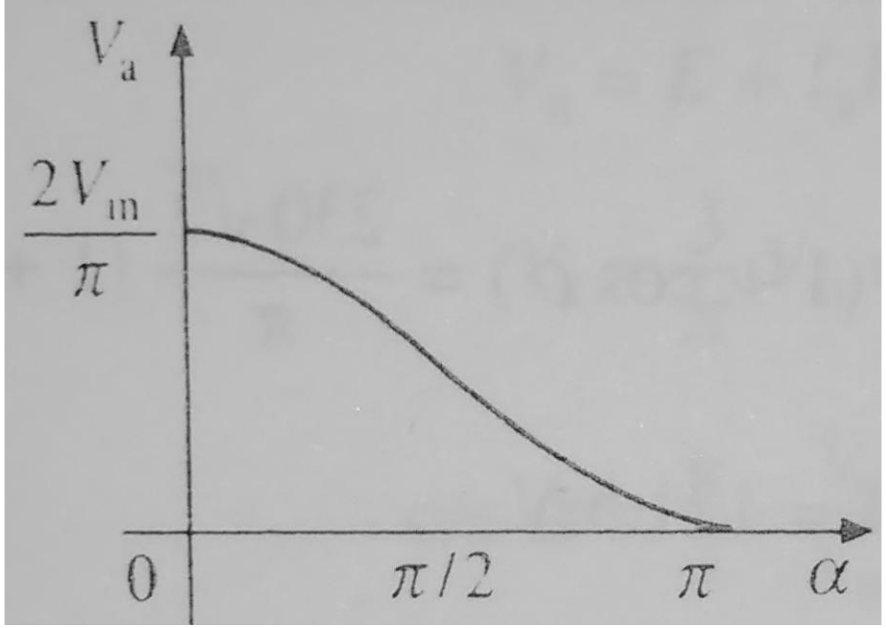
For Discontinuous conduction mode,



Average value of output voltage (Voltage across armature),

$$V_{avg} = \frac{1}{\pi}\left[\int_{\alpha}^{\pi} V_m Sin\,\omega t\, d\omega t + \int_{\beta}^{\pi+\alpha} E\, d\omega t\right] \quad i.e, \quad V_{avg} = \frac{1}{\pi}\left[V_m(1+Cos\alpha) + E(\pi+\alpha-\beta)\right]$$

- Here the average output voltage of the converter is always positive
- So regenerative braking is not possible and we can go for plugging (motor will work as generator during braking and electrical energy produced is wasted in an external resistance connected in series with armature during braking)

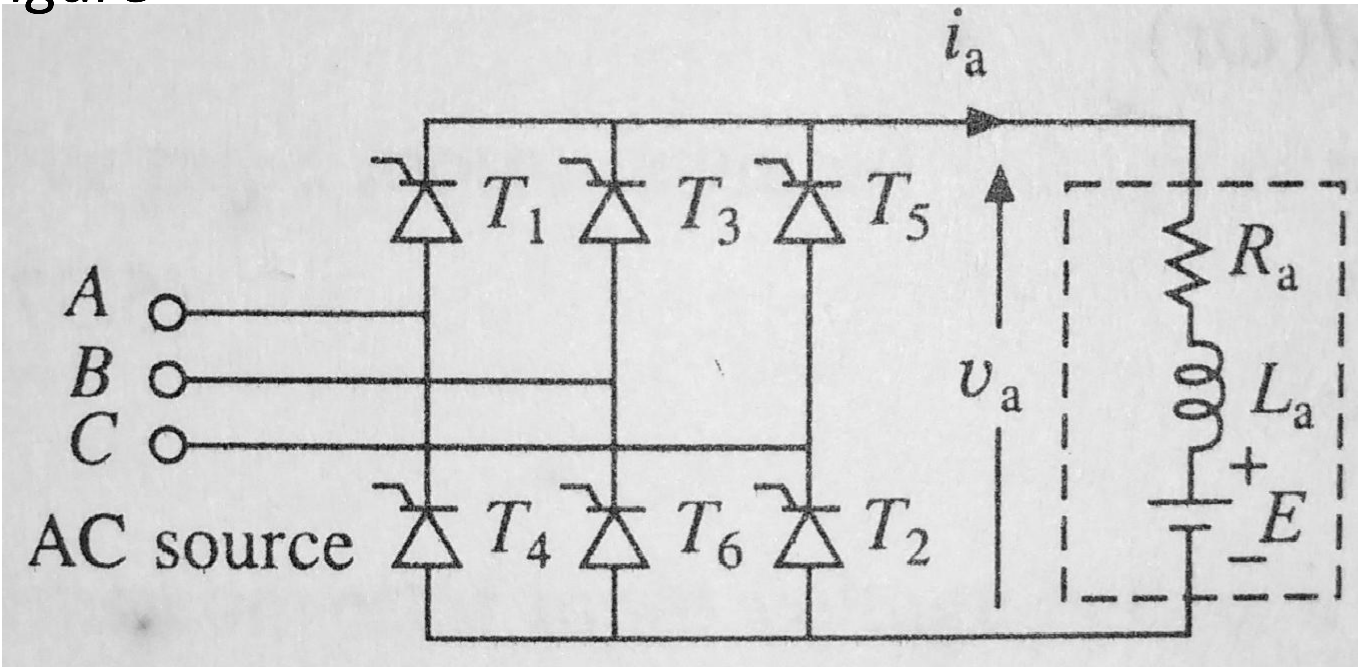


<u>Note</u>

- When compared to fully controlled converter, half controlled converter is cheap (using only 2 controlled devices), produces less ripple and got better power factor
- It gives control only in first quadrant

3 Phase fully controlled bridge rectifier fed separately excited DC motor Drive

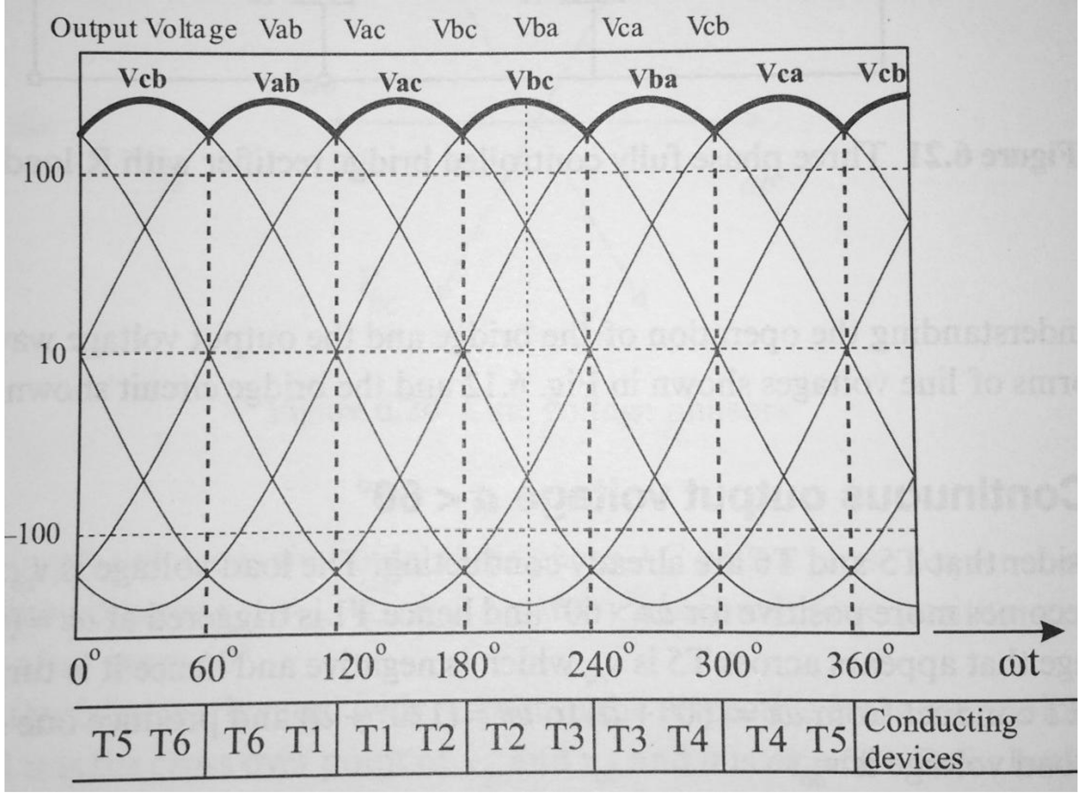
- A 3 phase fully controlled bridge rectifier fed separately excited DC motor drive is shown in figure



- Contain 6 thyristors T_1, T_2, T_3, ...T_6
- The supply voltage is sinusoidal 3 phase AC voltage with phase sequence ABC
- The output of rectifier is fed to the armature of DC motor
- Here 2 thyristors conducts at a time, one in the upper group and one in the lower group
- Each thyristor conducts for a duration of 120^0

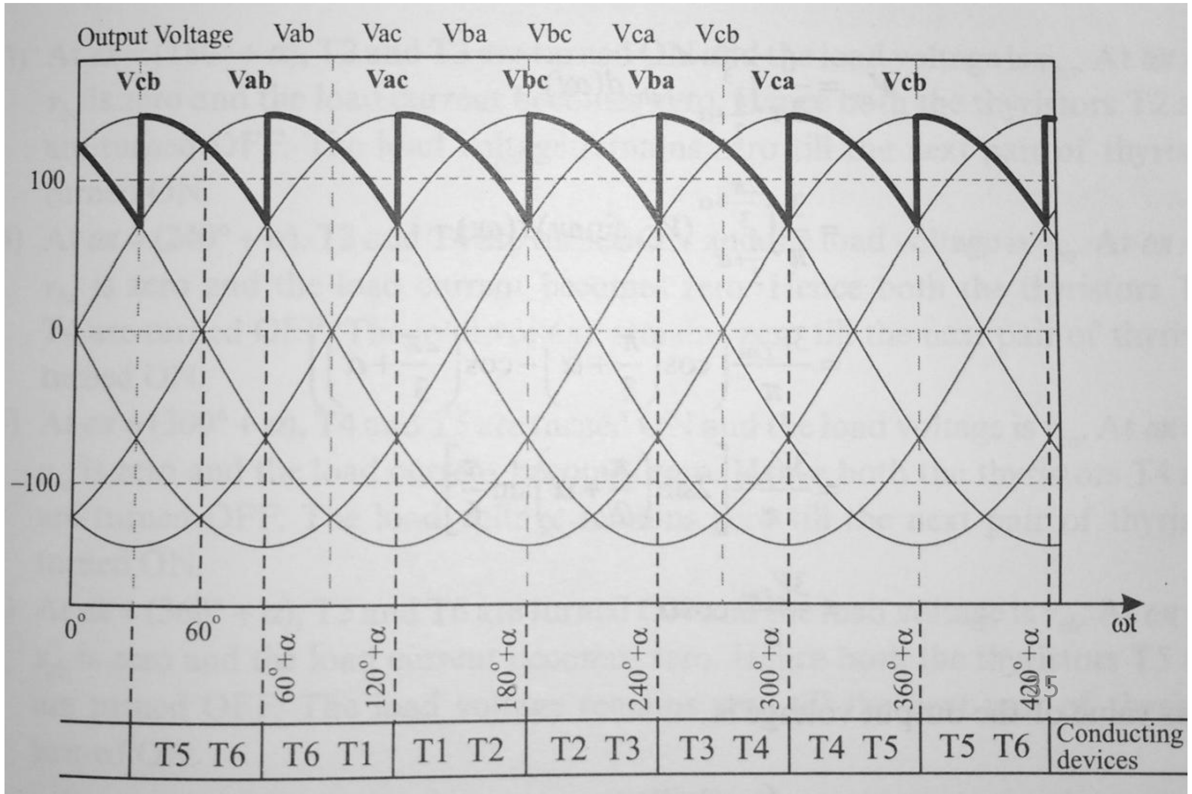
Working – for $\alpha = 30^\circ$

- Consider that T_5 & T_6 are already conducting, load voltage is V_{CB}
- The voltage V_{AB} become more positive for $\omega t > 60^\circ$ and hence T_1 is triggered at $\omega t = (60^\circ + \alpha)$, it starts conduction & T_5 gets turned OFF
- T_1 & T_6 conducts from $\omega t = (60^\circ + \alpha)$ to $\omega t = (120^\circ + \alpha)$, load voltage is V_{AB}
- At $\omega t = (120^\circ + \alpha)$, T_2 is triggered & is turned ON & T_6 gets turned OFF
- T_1 & T_2 conducts from $\omega t = (120^\circ + \alpha)$ to $\omega t = (180^\circ + \alpha)$, load voltage is V_{AC}
- At $\omega t = (180^\circ + \alpha)$, T_3 is triggered & is turned ON & T_1 gets turned OFF
- T_3 & T_2 conducts from $\omega t = 180^\circ + \alpha$ to $\omega t = (240^\circ + \alpha)$, load voltage is V_{BC}
- At $\omega t = (240^\circ + \alpha)$, T_4 is triggered & is turned ON & T_2 gets turned OFF
- T_3 & T_4 conducts from $\omega t = (240^\circ + \alpha)$ to $\omega t = (300^\circ + \alpha)$, load voltage is V_{BA}
- At $\omega t = (300^\circ + \alpha)$, T_5 is triggered & is turned ON & T_3 gets turned OFF
- T_5 & T_4 conducts from $\omega t = (300^\circ + \alpha)$ to $\omega t = (360^\circ + \alpha)$, load voltage is V_{CA}
- At $\omega t = (360^\circ + \alpha)$, T_6 is triggered & is turned ON & T_4 gets turned OFF
- T_5 & T_6 conducts from $\omega t = (360^\circ + \alpha)$ to $\omega t = (420^\circ + \alpha)$, load voltage is V_{CB}
- The cycle is then repeated

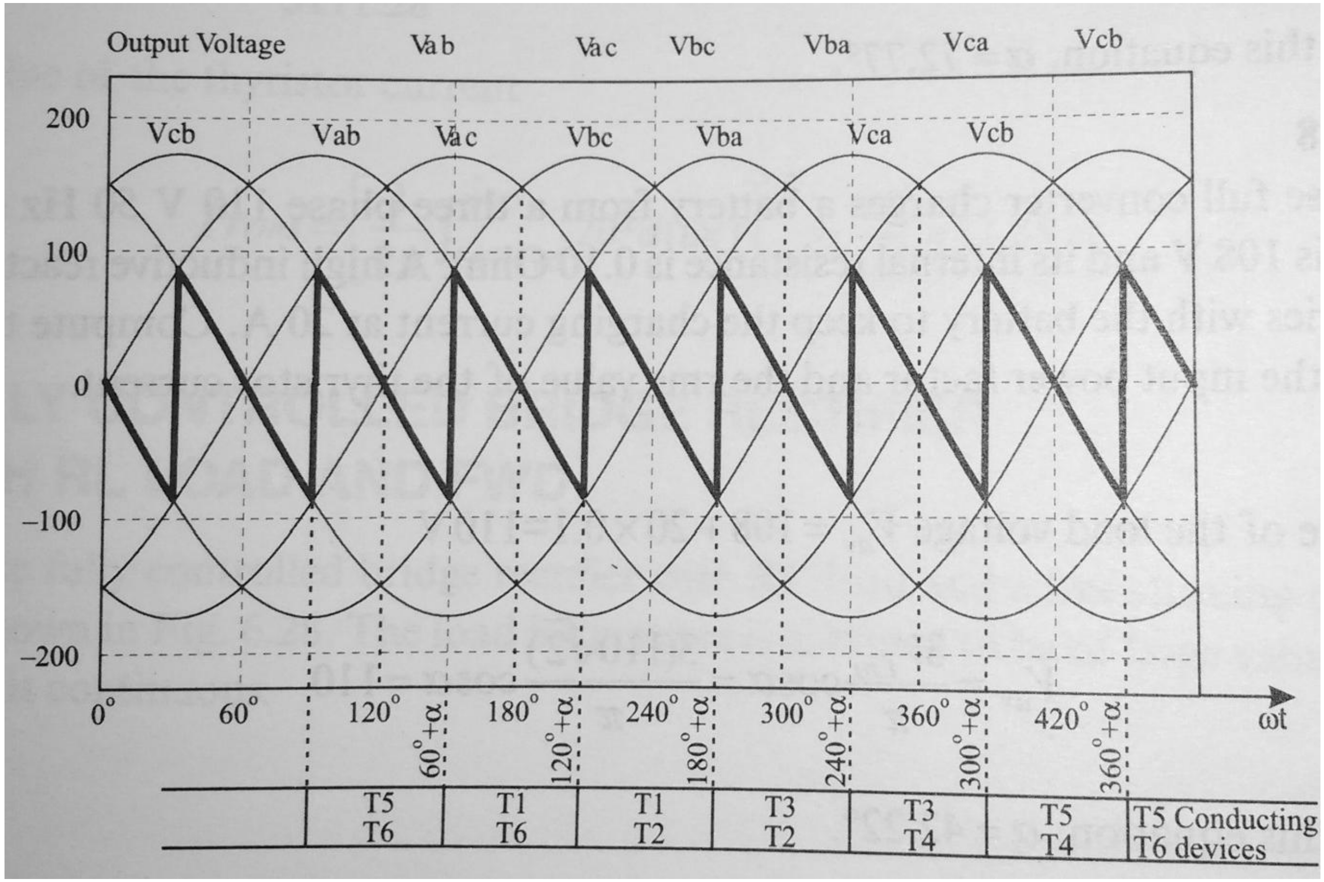


$\alpha = 0^\circ$

$\alpha = 30^\circ$



α = 90°



$$V_{avg} = \frac{1}{(\pi/3)} \int_{(\pi/3+\alpha)}^{(2\pi/3+\alpha)} V_{mL} Sin\omega t\, d\omega t \quad = \frac{3V_{mL}}{\pi}(-Cos\,\omega t)\Big]_{(\pi/3+\alpha)}^{(2\pi/3+\alpha)}$$

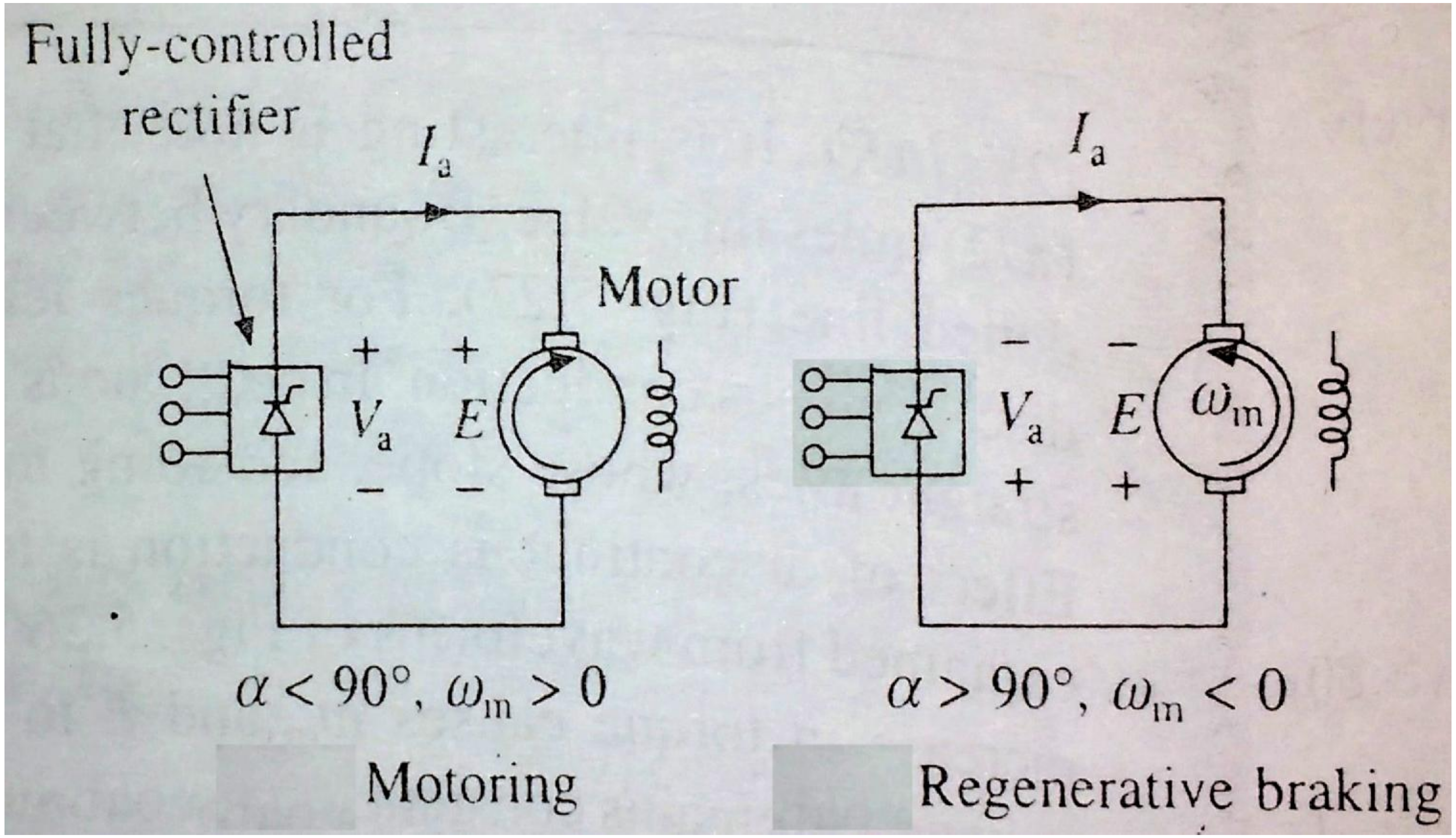
$$i.e, \quad V_{avg} = \frac{3V_{mL}}{\pi} Cos\alpha$$

ie, by varying α, average value of output voltage can be varied, and hence speed of the motor.

This drive can operate in 2 quadrants

1. *Quadrant I operation* (forward motoring)

   for (0<α<90), the average output voltage of rectifier is positive & V_a>E. Now the machine will work as a motor

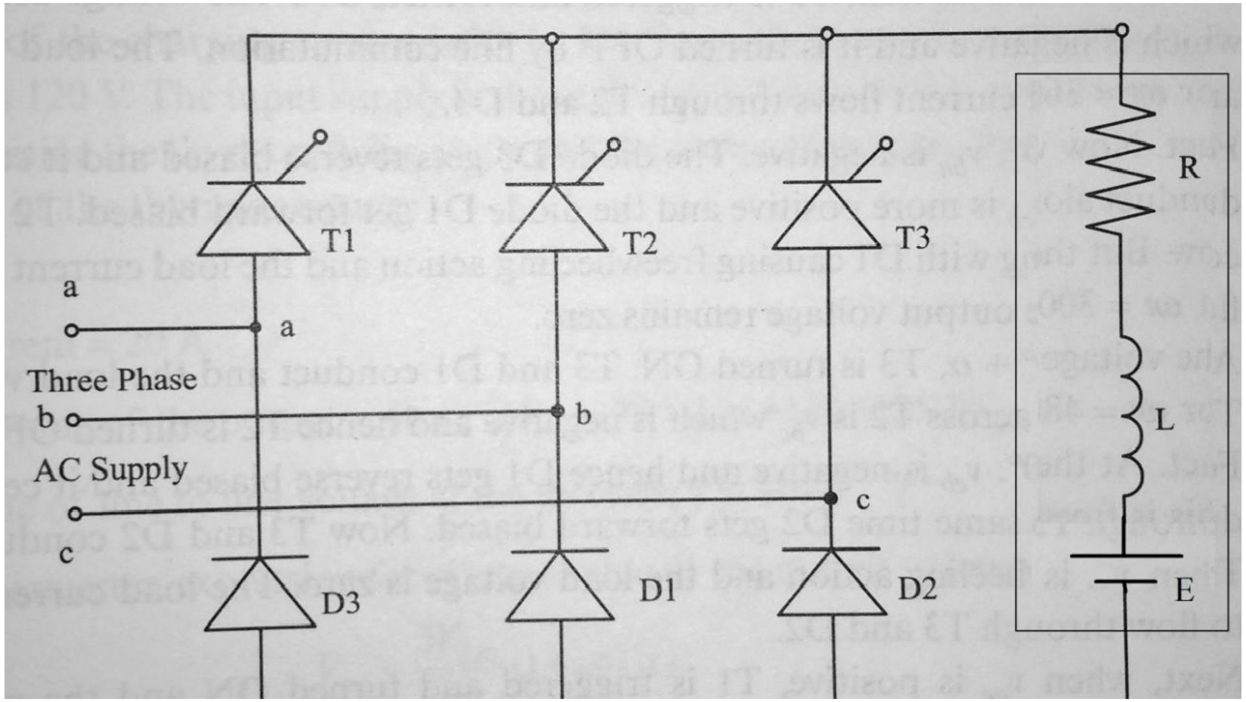


2. *Quadrant IV operation* (reverse regenerative braking)

   for (90<α<180), the average output voltage of rectifier is negative & V_a<E. Now the motor will work in regenerative braking mode by supplying energy to the source & rectifier will work as an inverter.

3 Phase half controlled bridge rectifier fed separately excited DC motor Drive

- A 3 phase half controlled bridge rectifier fed separately excited DC motor drive is shown in figure



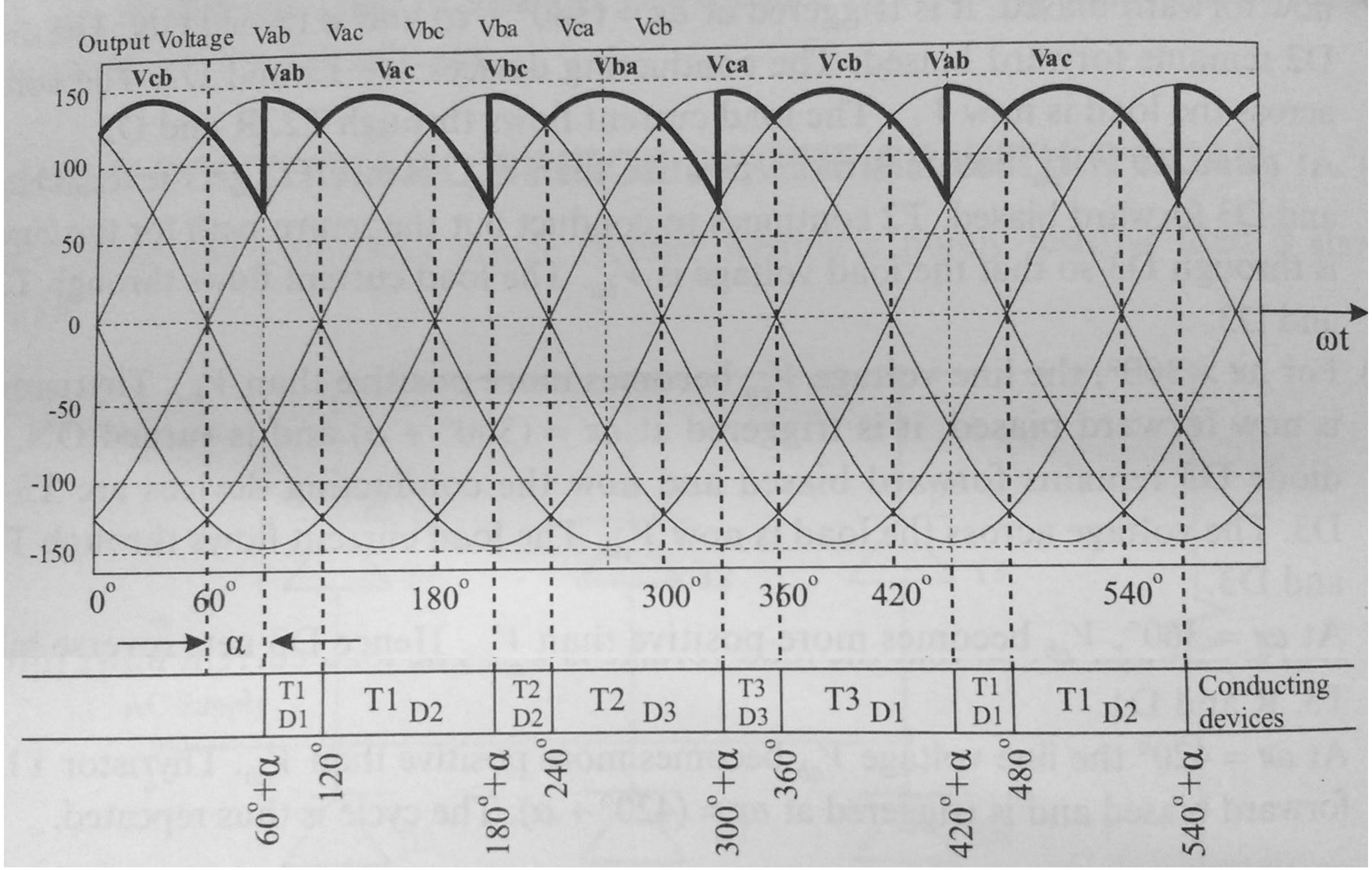
- Contain 3 thyristors & 3 Diodes

  T_1, T_2, T_3 & D_1, D_2, D_3
- The supply voltage is sinusoidal 3 phase AC voltage with phase sequence ABC
- The output of rectifier is fed to the armature of a DC motor
- Here 1 thyristor & 1 Diode conducts at a time
- Each thyristor conducts for a duration of 120°

Working – for $\alpha = 30^\circ$

- The voltage V_{AB} become more positive for $\omega t>60^\circ$ and hence T_1 is triggered at $\omega t=(60^\circ + \alpha)$, it starts conduction & T_5 gets turned OFF. Diode D_1 is also forward biased & it conducts
- T_1 & D_1 conducts from $\omega t=(60^\circ + \alpha)$ to $\omega t=120^\circ$, load voltage is V_{AB}
- At $\omega t=120^\circ$, V_{AC} become more positive than V_{AB}. Hence D_1 gets reverse biased and D_2 gets forward biased.
- T_1 & D_2 conducts from $\omega t=120^\circ$ to $\omega t=(180^\circ + \alpha)$, load voltage is V_{AC}
- At $\omega t=(180^\circ + \alpha)$, T_2 is triggered & is turned ON & T_1 gets turned OFF
- T_2 & D_2 conducts from $\omega t=180^\circ + \alpha$ to $\omega t=240^\circ$, load voltage is V_{BC}
- At $\omega t=240^\circ$, V_{BA} become more positive than V_{BC}. Hence D_2 gets reverse biased and D_3 gets forward biased.
- T_2 & D_3 conducts from $\omega t=240^\circ$ to $\omega t=(300^\circ + \alpha)$, load voltage is V_{BA}
- At $\omega t=(300^\circ + \alpha)$, T_3 is triggered & is turned ON & T_2 gets turned OFF
- T_3 & D_3 conducts from $\omega t=(300^\circ + \alpha)$ to $\omega t=360^\circ$, load voltage is V_{CA}
- At $\omega t=360^\circ$, V_{CB} become more positive than V_{CA}. Hence D_3 gets reverse biased and D_1 gets forward biased.
- T_3 & D_3 conducts from $\omega t=360^\circ$ to $\omega t=(420^\circ + \alpha)$, load voltage is V_{CB}
- The cycle is then repeated.

For α = 30◦



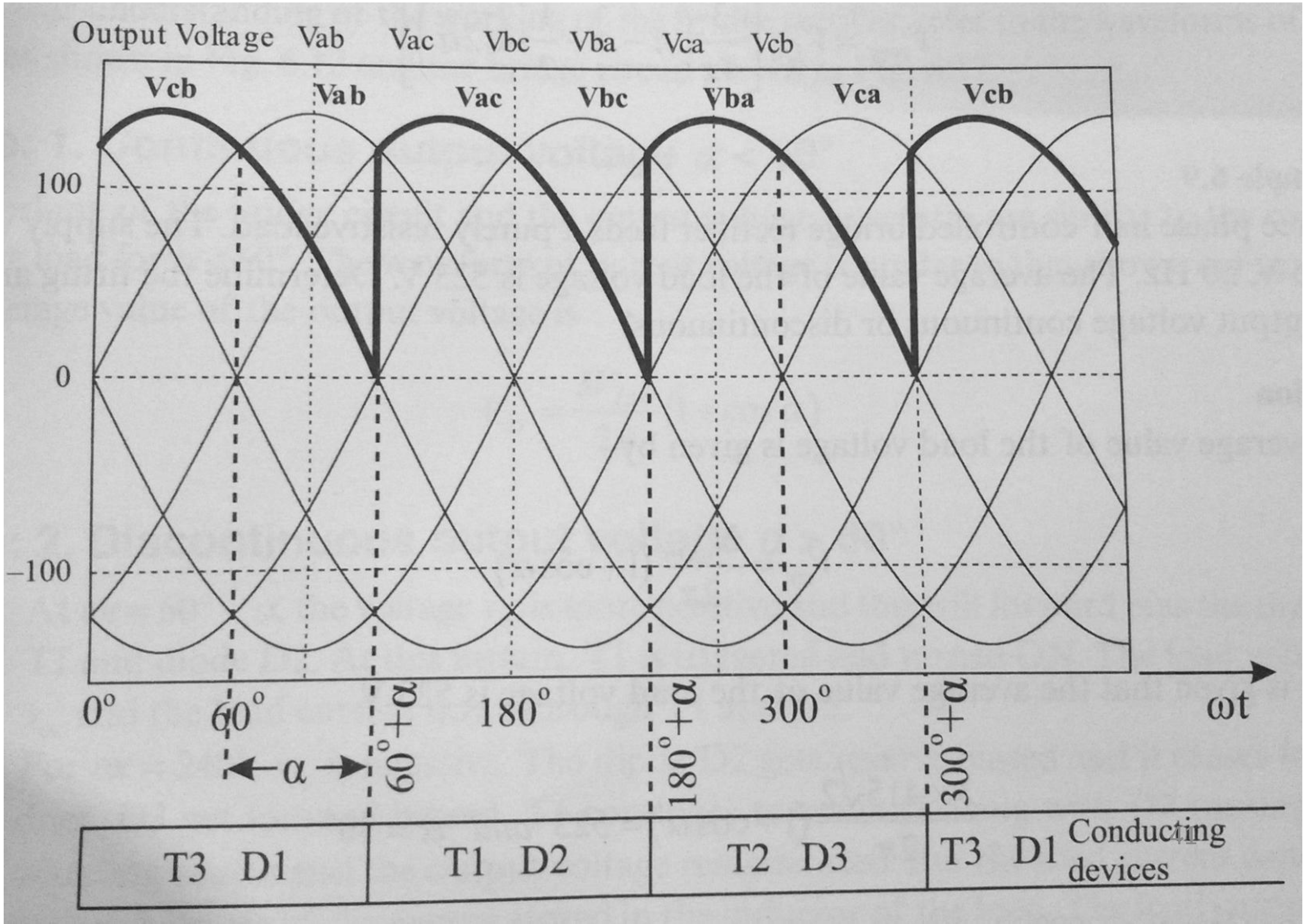
Average value of output voltage (Voltage across armature),

$$V_{avg} = \frac{1}{2\pi/3}\left[\int_{\pi/3+\alpha}^{2\pi/3} V_m Sin\,\omega t\, d\omega t + \int_{2\pi/3}^{\pi+\alpha} V_m Sin(\omega t - \pi/3)\, d\omega t\right]$$

$$= \frac{3V_m}{2\pi}\left\{-Cos\,\omega t\right]_{\pi/3+\alpha}^{2\pi/3}\left.\right\} + \frac{3V_m}{2\pi}\left\{-Cos(\omega t - \pi/3)\right]_{2\pi/3}^{\pi+\alpha}\left.\right\}$$

i.e, $V_{avg} = \frac{3V_m}{2\pi}(1+Cos\alpha)$ (i.e, by varying α, the average value of output voltage applied to armature can be controlled & hence speed of the motor)

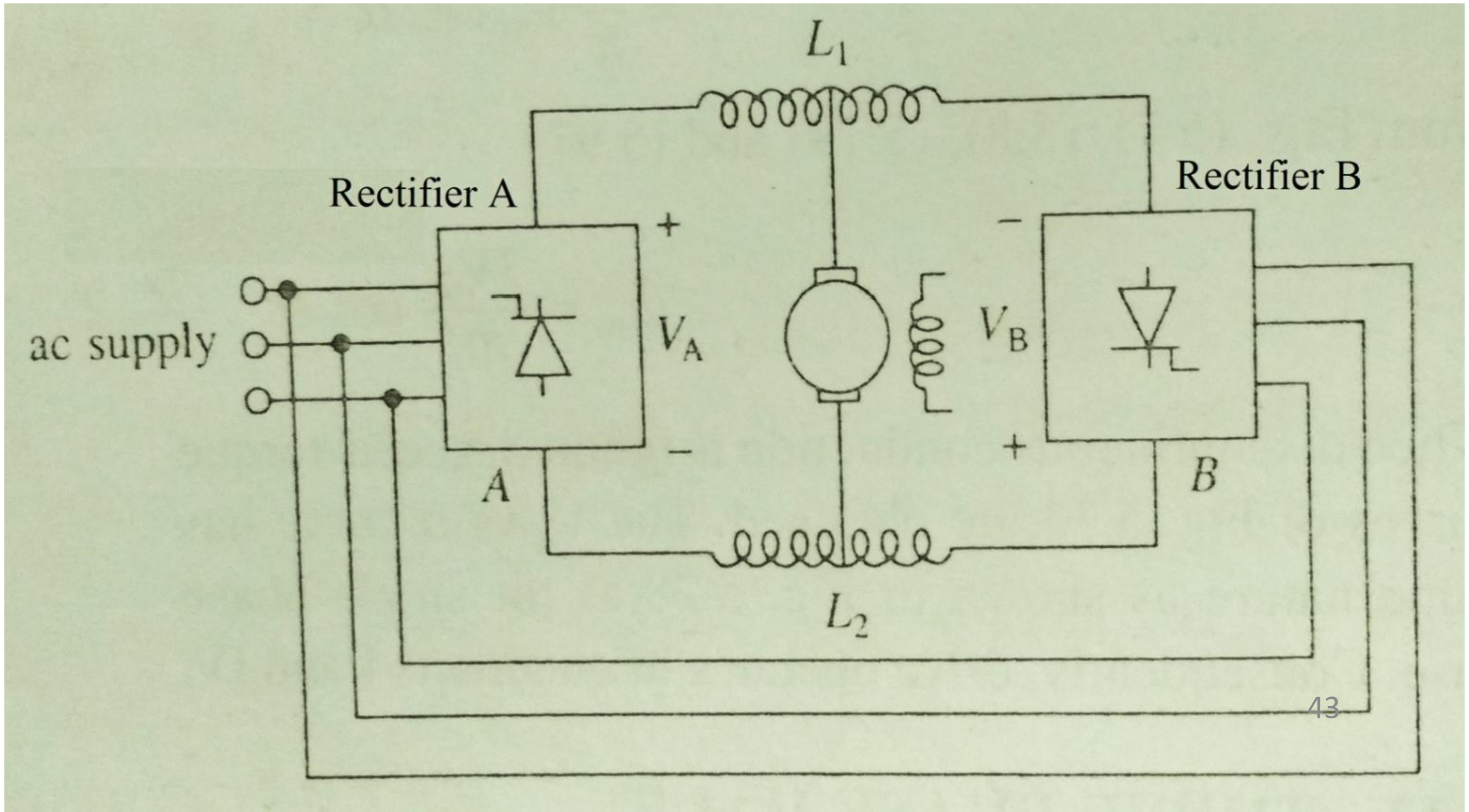
α = 60°



- This is a single quadrant drive (I[st] quadrant – forward motoring)
- Here the average output voltage of the converter is always positive
- So regenerative braking (IV[th] quadrant operation) is not possible and we can go for plugging (motor will work as generator during braking and electrical energy produced is wasted in an external resistance connected in series with armature during braking)

Dual converter fed Separately excited DC motor Drive

- A dual converter consist of two fully controlled rectifiers connected in anti parallel across the armature of DC motor
- For power rating upto 10kW, single phase fully controlled rectifiers are used
- For higher ratings, 3 phase fully controlled rectifiers are used
- Here 4 quadrant operation is possible
- A 3 phase dual converter fed DC motor drive system is shown in figure



- The operation of 3 phase & 1 phase dual converter remains same. The difference is in the rectifier configuration and supply
- Here Rectifier A which provides a positive motor current & voltage in either direction, allows motor control in quadrants I & IV
- Rectifier B provides a negative motor current & voltage in either direction, allows motor control in quadrants III & II
- There are *2 modes of control for a Dual converter*

1. **Non simultaneous or Non circulating current control method**

- Here one rectifier is operated at a time.
- Consequently no circulating current flows & inductors L_1 & L_2 are not required
- This eliminates losses associated with circulating current & weight & volume associated with inductors
- Here automatic control of firing pulses is done & control is complicated

When rectifier A operates alone,

- If firing angle α_A is varied from 0 to $\pi/2$, the rectifier A acts as a rectifier itself & machine operates as motor in forward direction (Quadrant I operation)
- If firing angle α_A is varied from $\pi/2$ to π, the rectifier A acts as an inverter & machine operates as generator in reverse direction (Quadrant IV operation)

When rectifier B operates alone,

- If firing angle α_B is varied from 0 to $\pi/2$, the rectifier B acts as a rectifier itself & machine operates as motor in reverse direction (Quadrant III operation)
- If firing angle α_B is varied from $\pi/2$ to π, the rectifier B acts as an inverter & machine operates as generator in forward direction (Quadrant II operation)

Speed reversal is carried out as follows,

- When operating in Quadrant-I, rectifier A will be supplying the motor & B will not be operating
- Firing angle of rectifier A is set at the highest value
- Now rectifier A work as an inverter & forces the armature current to zero
- After zero current is sensed, a dead time of 2 to 10msec is provided to ensure turn OFF of thyristors of rectifier A
- Now firing pulses are given to rectifier B
- At first firing angle is set at the highest value, so that motor brakes, speed reduces to zero
- As speed reduces control loop adjusts firing angle continuously so that motor accelerates in the reverse direction

2. Simultaneous or Circulating current control method

- Here both the rectifiers are controlled together
- In order to avoid circulating current between rectifiers, they are operated to produce same DC output voltage across the motor terminal

  Thus $V_A+V_B = 0$, i.e, $(3V_m/\pi)\text{Cos}\alpha_A+(3V_m/\pi)\text{Cos}\alpha_B = 0$

  i.e, $\text{Cos}\alpha_A+\text{Cos}\alpha_B = 0$ i.e, $\alpha_A+\alpha_B = 180$
- If the above relation is satisfied, DC circulating current will be zero
- But due to difference in instantaneous output voltage of rectifiers, there will be an AC circulating current
- Inductors L_1 & L_2 are added in the circuit to reduce AC circulating current

Operation

- When firing angle α_A is varied from 0 to $\pi/2$ and firing angle α_B is varied from $\pi/2$ to π, Rectifier A operates as a rectifier & Rectifier B operates as an inverter

The machine will either operates as a motor in Quadrant I by taking power from Rectifier A or as a generator in quadrant II by feeding back to supply through Rectifier B

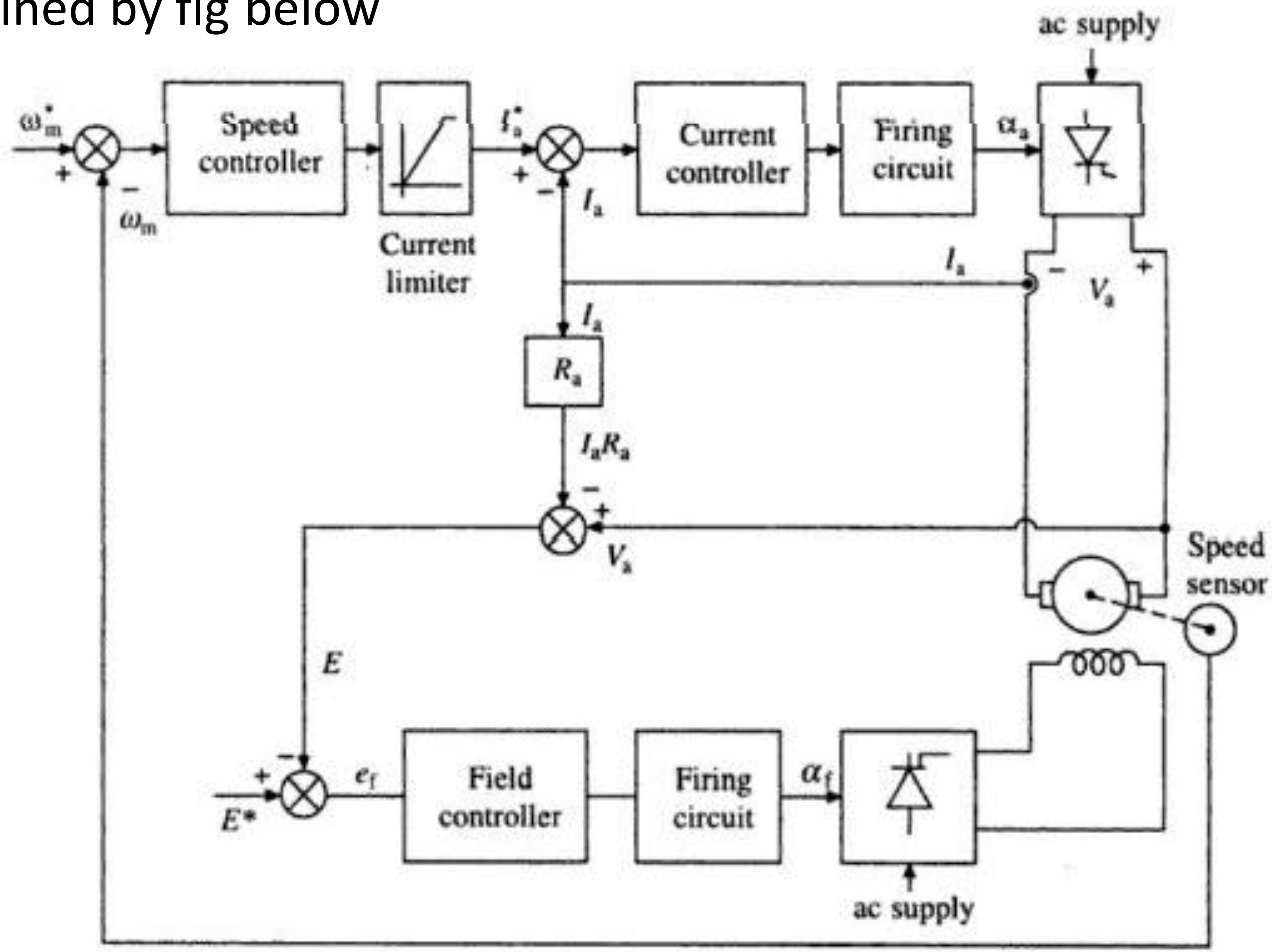
- When firing angle, α_A is varied from $\pi/2$ to π and firing angle, α_B is varied from 0 to $\pi/2$, Rectifier A operates as an inverter & Rectifier B operates as a rectifier. The machine will either operates in Quadrant IV or III. The machine will either operates as a motor in Quadrant III by taking power from Rectifier B or as a generator in quadrant IV by feeding back to supply through Rectifier A

The speed reversal is carried out as follows

- When operating in Quadrant I, rectifier A will be rectifying & rectifier B will be inverting.
- For speed reversal α_A is increased & α_B is decreased. The motor back emf exceeds V_A & V_B
- The armature current shifts to rectifier B & motor operates in Quadrant II
- The control loop controls α_A & α_B instantaneously.

Closed loop control of separately excited DC motor drive

- The closed loop speed control above & below base speed can be explained by fig below



- The drive employs an inner current control loop & an outer speed control loop
- This drive can operate at a constant field current & variable armature voltage below base speed and at a constant armature voltage & variable field current above base speed
- Both armature & field are supplied from fully controlled rectifiers

Operation below base speed

- Here he firing angle of field rectifier is maintained at zero, applying rated voltage to field
- This ensures rated field current and excitation for motor operation below base speed
- When actual speed is low compared to reference speed, the speed error is high
- As a result current limiter saturates & sets the current reference at maximum permissible value
- Now the drive accelerates at maximum available current & torque .

- When actual speed reaches close to reference speed, current limiter desaturates & speed settles down to reference speed

Operation above base speed

- The firing angle of armature rectifier is reduced to increase V_a.
- The motor accelerates, E increases, e_f decreases & field current reduces
- Speed increases & I_f decreases until motor speed becomes equal to reference speed

DC series motor drive for traction applications

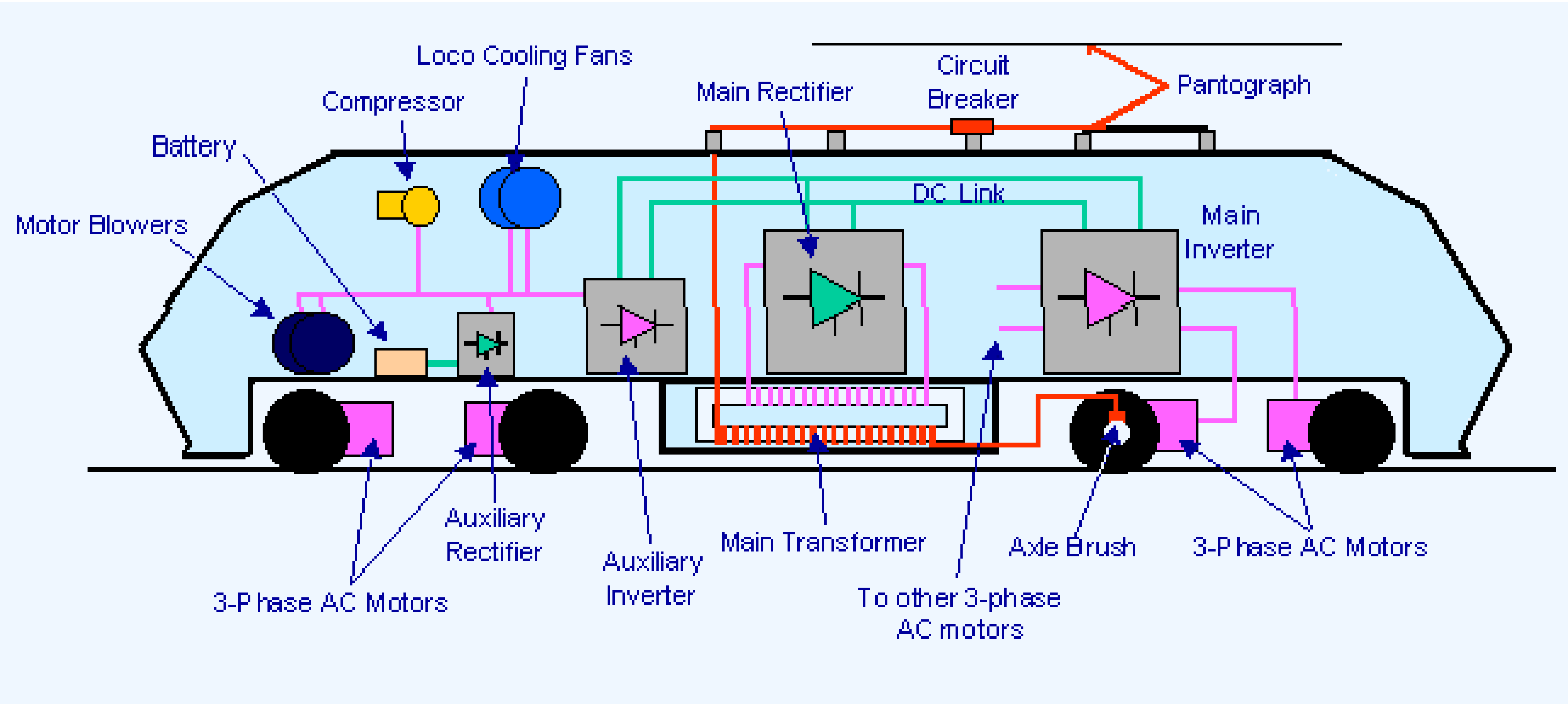
Electric traction

- Electric traction – used to transport men & material from one place to another
- It involve electric train, electric buses, trams & trolleys

Electric trains

- Electric trains run on fixed rails
- They are classified into main line train & suburban train
- Suburban train is used for transporting men within a city or between cities located at small distances
- All other services come under main line service
- In an electric train, the driving motor & power modulators are housed in the locomotive
- An overhead transmission line is used to supply power to the train
- Electric traction is classified into single phase AC & DC depending on the supply
- In India, 25kV, 50Hz AC supply is used for AC traction
- 1500V DC traction is used in Bombay – Igatpuri section
- The schematic of an electric locomotive is shown in next slide.

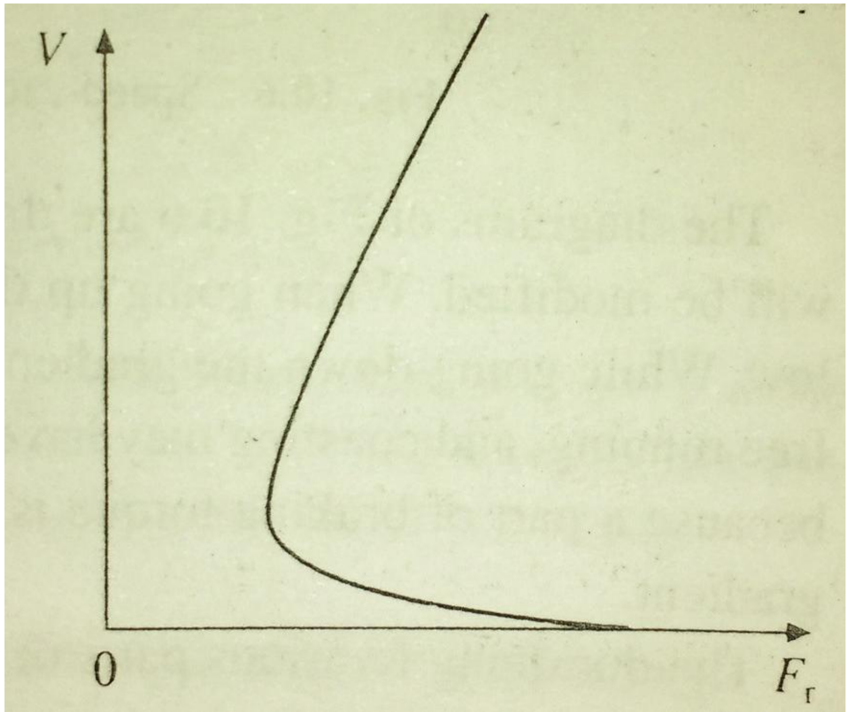
- A pantograph is used to collect power from contact wire
- Inside locomotive, a transformer will step down the voltage & fed to power modulator which in turn powers the driving motors (AC or DC motors)
- Locomotive power rating can be as high as 6000HP & more
- Powering such large 1 phase load creates unbalances in the system



- To avoid unbalances, track supply is divided into different sections & connected to different phases
- If 3 phase system has high capacity, the unbalances are not affected

Nature of traction load

- When a train runs a number of frictional forces like bearing friction, friction between wheel & rail, air friction etc. opposes the motion
- All these frictional forces together called train resistance
- The variation in train resistance with speed is shown in figure
- In train resistance, striction has a large value & influence of air friction is high, which varies as the square of speed
- When deciding torque requirements of driving motors, torque components required to provide acceleration & to overcome gravity must be considered



Important features of traction drives

- Large torque is required during start & acceleration in order to accelerate heavy mass
- The motor is subjected to torque overloads during acceleration
- Because of economic reasons, single phase supply is used in AC traction
- The locomotive rating can be 6000HP & higher
- The supply has sharp voltage fluctuations
- The harmonics injected into the source, both in DC & AC traction can cause mal operation of signals & interference in telephone lines
- Dynamic braking is widely used
- Regenerative braking is used when the energy saved is large enough to justify the additional cost of drive & transmission lines
- Wheel slip should be avoided
- Suburban trains have more than one motor coach. Electrical interconnection is provided between the two so that the drive for all motor coaches can be controlled from the master controller in the motor coach in the front.

Conventional DC & AC traction drives

- In India, conventionally ***DC series motors*** are used in ***traction drives***
- Conventional DC/AC traction drives are generally classified into two,
    1. DC/AC traction without controlled converters
    2. DC/AC traction with controlled converters

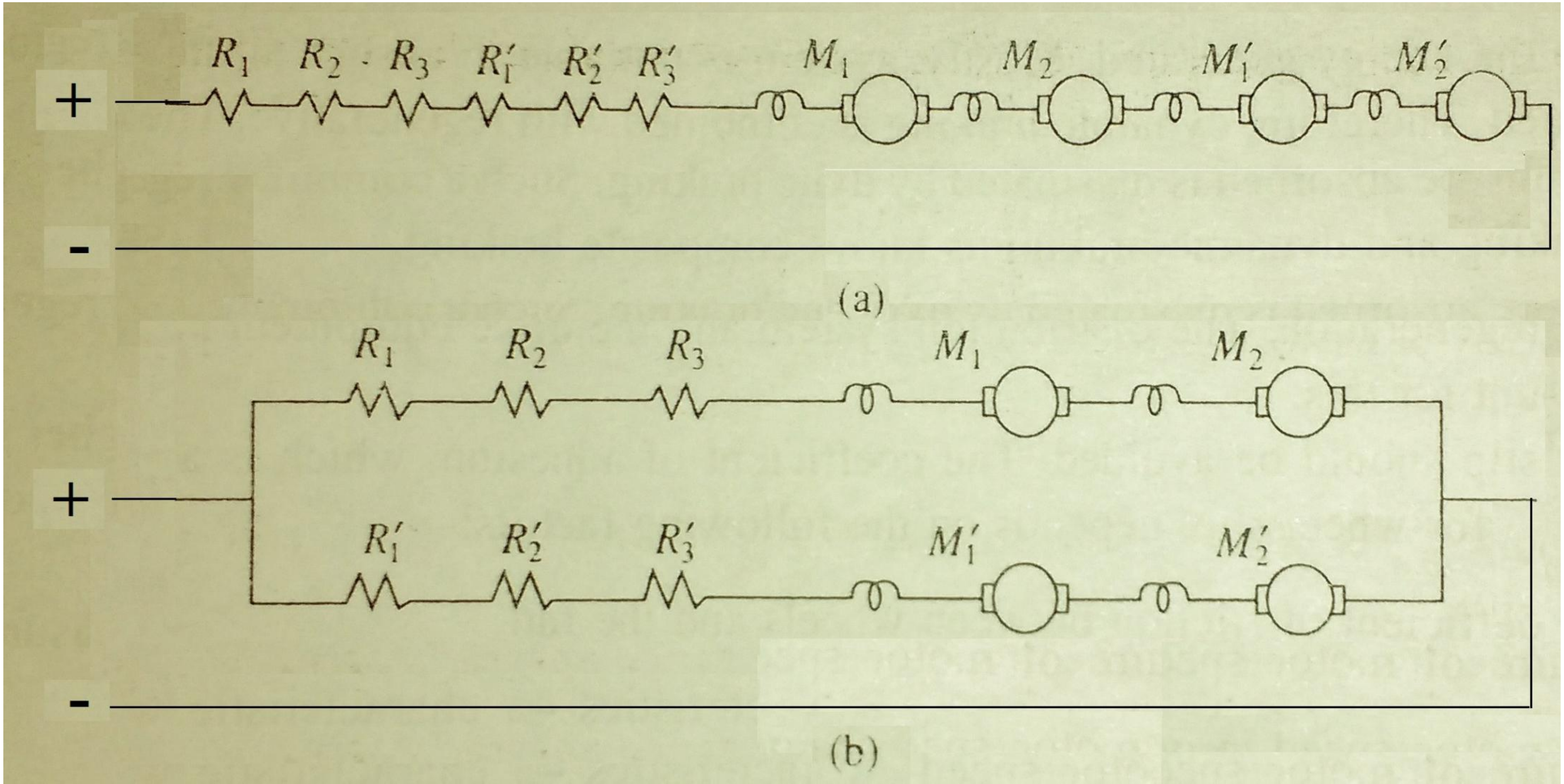
1. DC/AC traction without controlled converters

- Here the traction drives does not use any controlled converters

a) DC traction drive employing resistance control

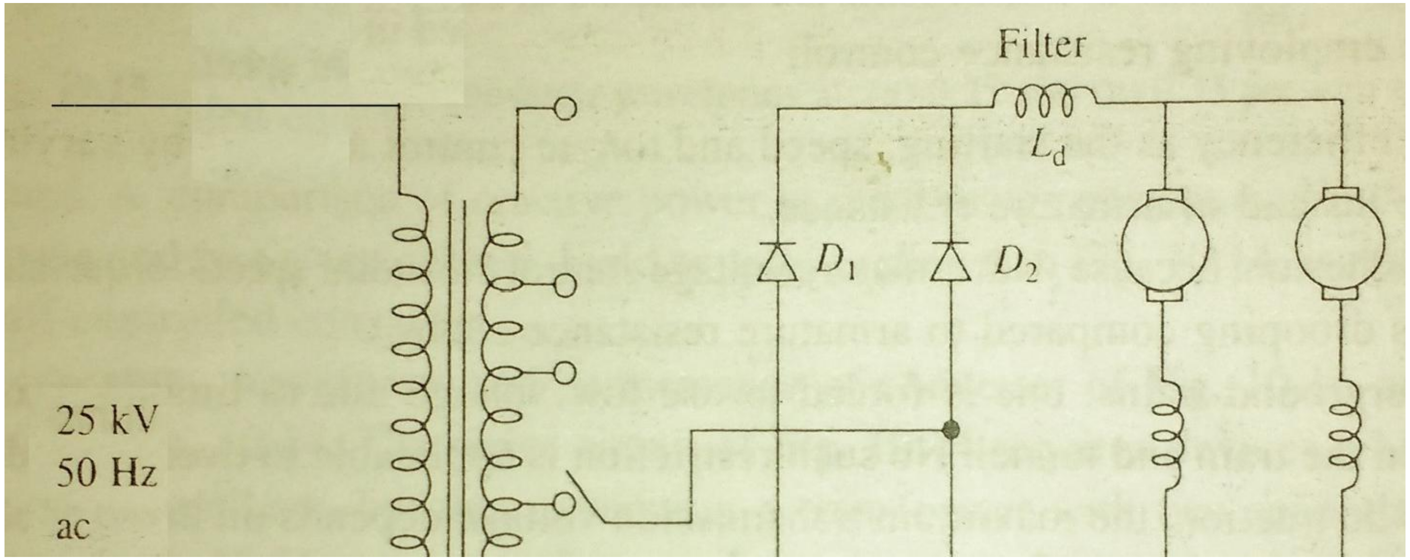
- The DC supply is usually 1500V/750V.
- Uses DC series motors with rating 750V/375V
- Two series motors are permanently connected in series to form one pair
- The arrangement is shown in the figure
- Here, to get a speed variation from 0 to half rated speed, the motor pairs are connected in series as shown in figure (a)
- The speed variation is achieved by varying the resistances.

- To get a speed variation from 0 to rated speed, the motor pairs are connected in parallel as shown in figure (b)
- The speed variation is achieved by varying the resistance
- This method got poor efficiency & require frequent maintenance due to the presence of moving contacts



b) AC traction drive using transformer with on load tap changer

- Here a step down transformer with suitable tapings are used
- The transformer secondary is connected to a diode rectifier
- DC output of rectifier is fed to DC series motors
- The speed control is achieved by varying the input AC voltage of diode rectifier by changing transformer taps
- This method got high efficiency, high initial cost, frequent maintenance.



2. DC/AC traction with controlled converters

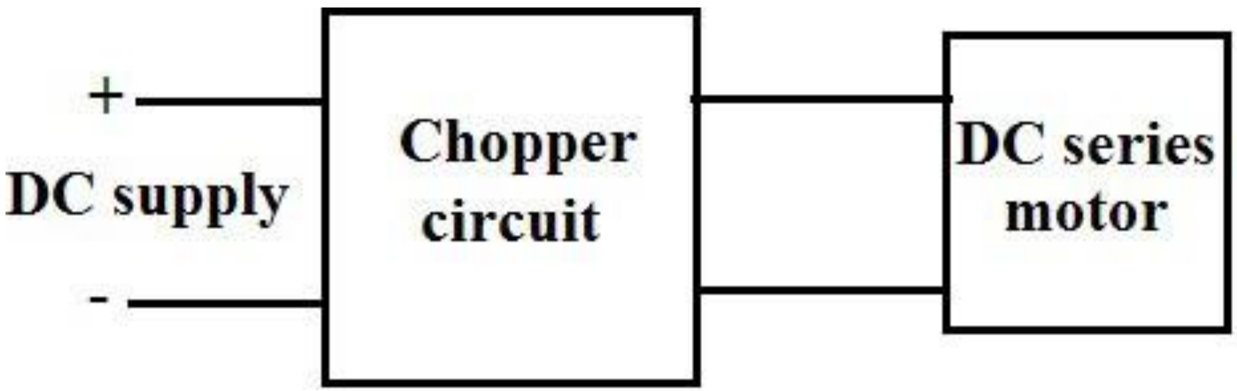
- Here controlled converters are used for controlling the drive

Advantages

- High efficiency
- Low maintenance
- Higher acceleration & deceleration
- Flexible control
- Longer life

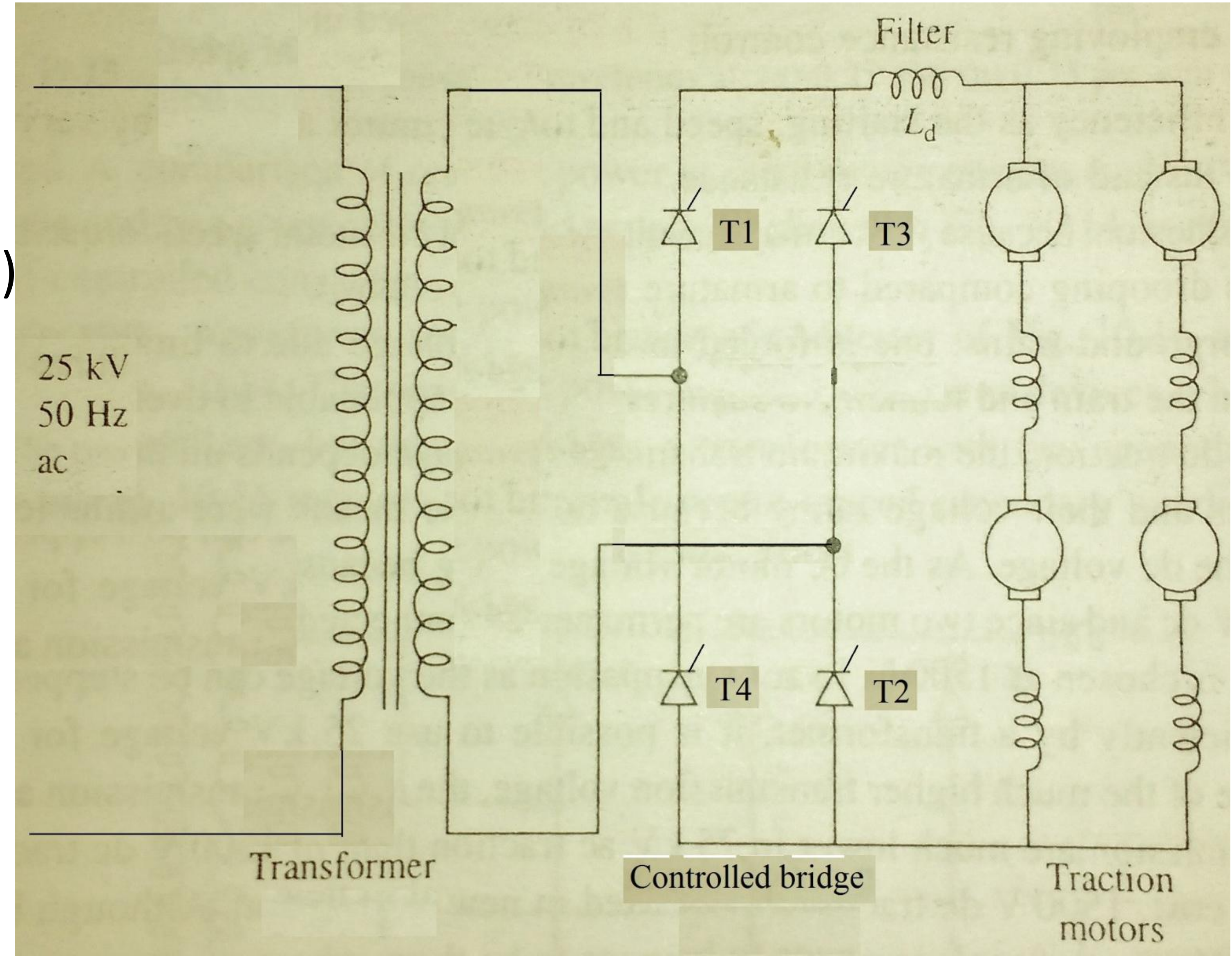
a) DC traction using chopper

- here chopper is used to get a variable DC supply from a fixed DC input
- variable DC from chopper is fed to DC series motor



b) AC traction using controlled rectifiers

- Here controlled rectifiers are used to convert input AC to DC
- Now this DC is fed to DC series motor
- DC output voltage of rectifier is controlled by varying firing angle of rectifier
- A transformer is used to step down the input AC (25kV) voltage to a suitable value



MODULE - III

DC MOTOR DRIVES - CHOPPER FED DC MOTOR DRIVES,
CYCLOCONVERTER FOR DRIVE APPLICATIONS

Chopper fed DC Drives

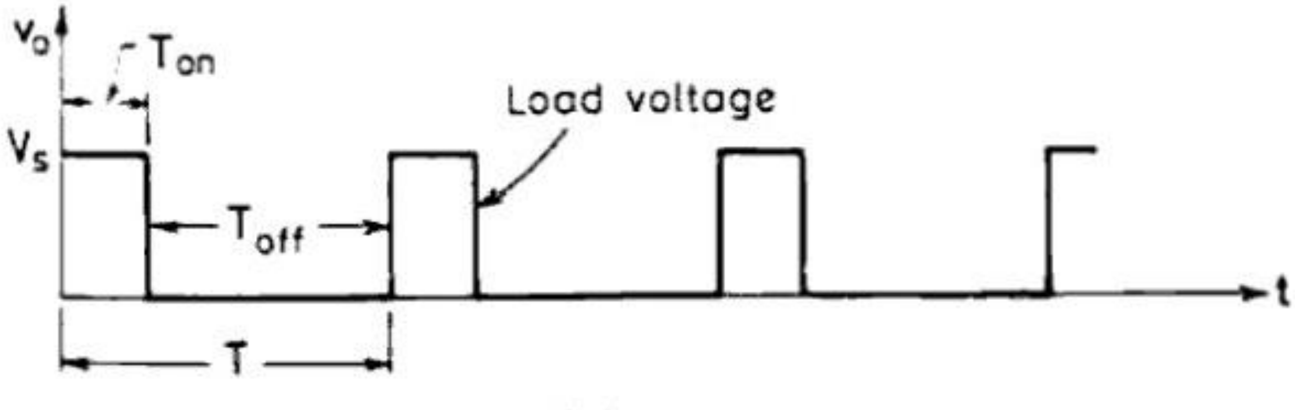
- Choppers are DC to DC converters used to get a variable DC voltage from a fixed DC source
- Self commutated devices like MOSFET, IGBT, power transistors etc are preferred over thyristors for building choppers because they can be commutated by a low power control signal & do not need a commutation circuit
- These devices can be operated at a higher frequency & at higher frequency motor performance improves
- Here regenerative braking can be carried out at low speeds

Control strategies for Chopper

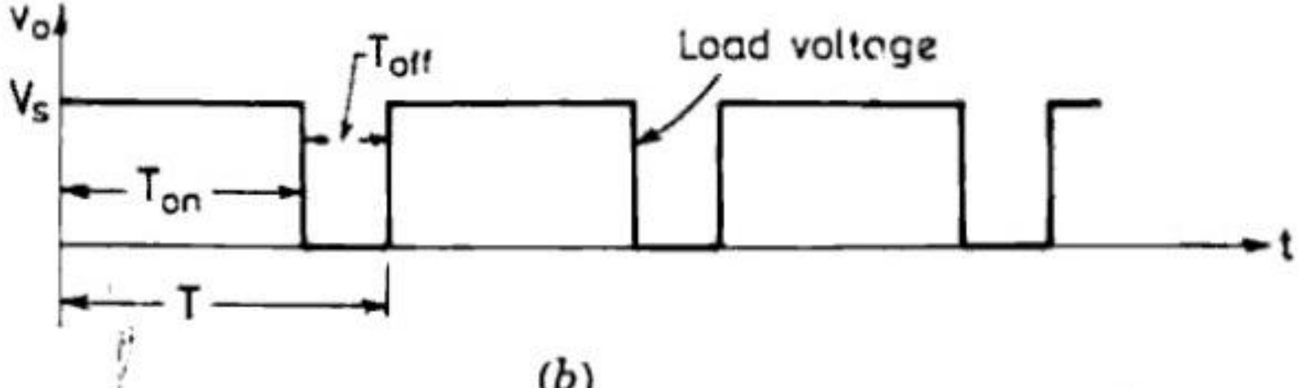
a) Time ratio control

- In this control scheme, as the name suggests time ratio T_{on}/T is varied
- This is realised using two different strategies

1. *Constant frequency system* – In this system, the on time (T_{on}) is varied and T is kept constant. This method of control is called pulse width modulation scheme. From fig (a) & (b) we can see how the output voltage is varied when T is kept constant and T_{on} is varied

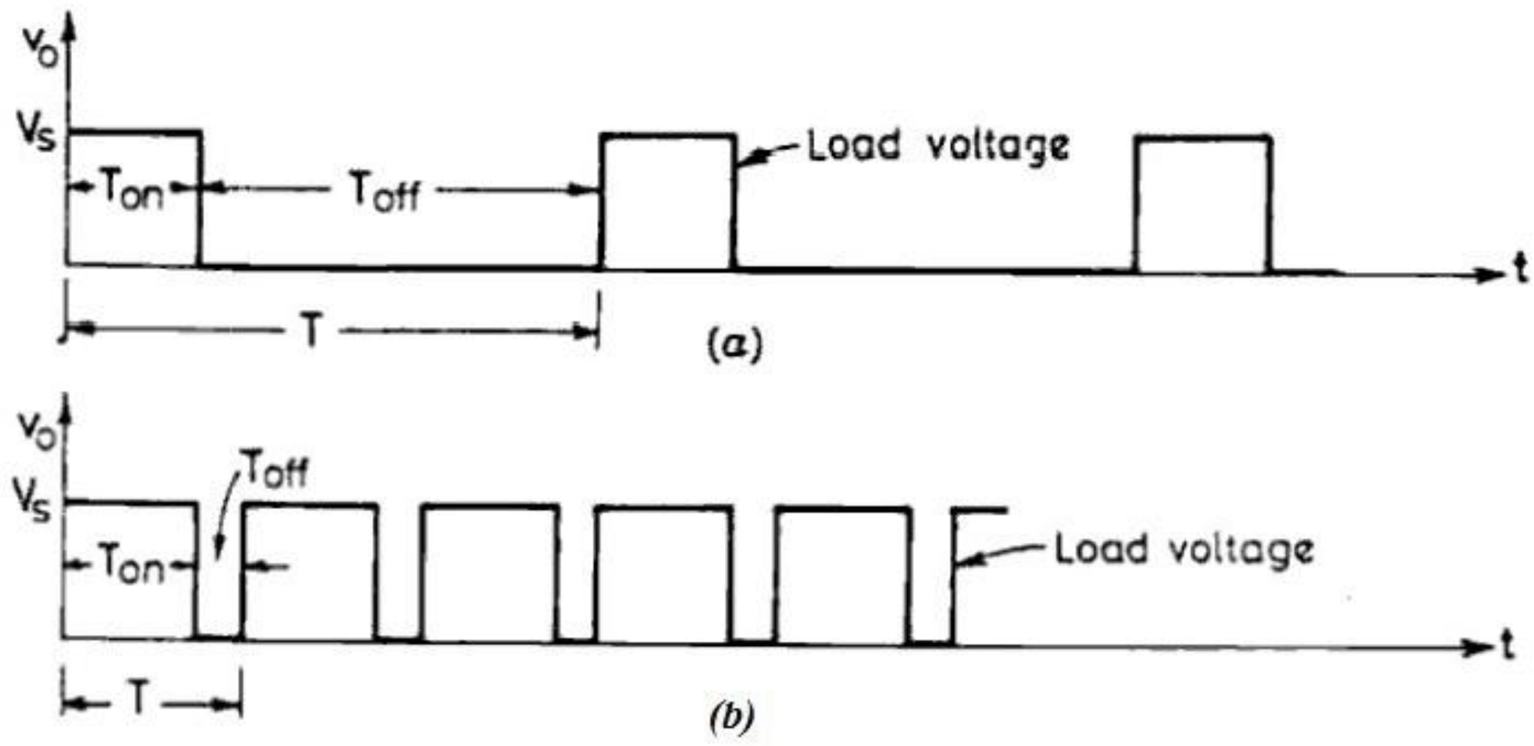


(a)



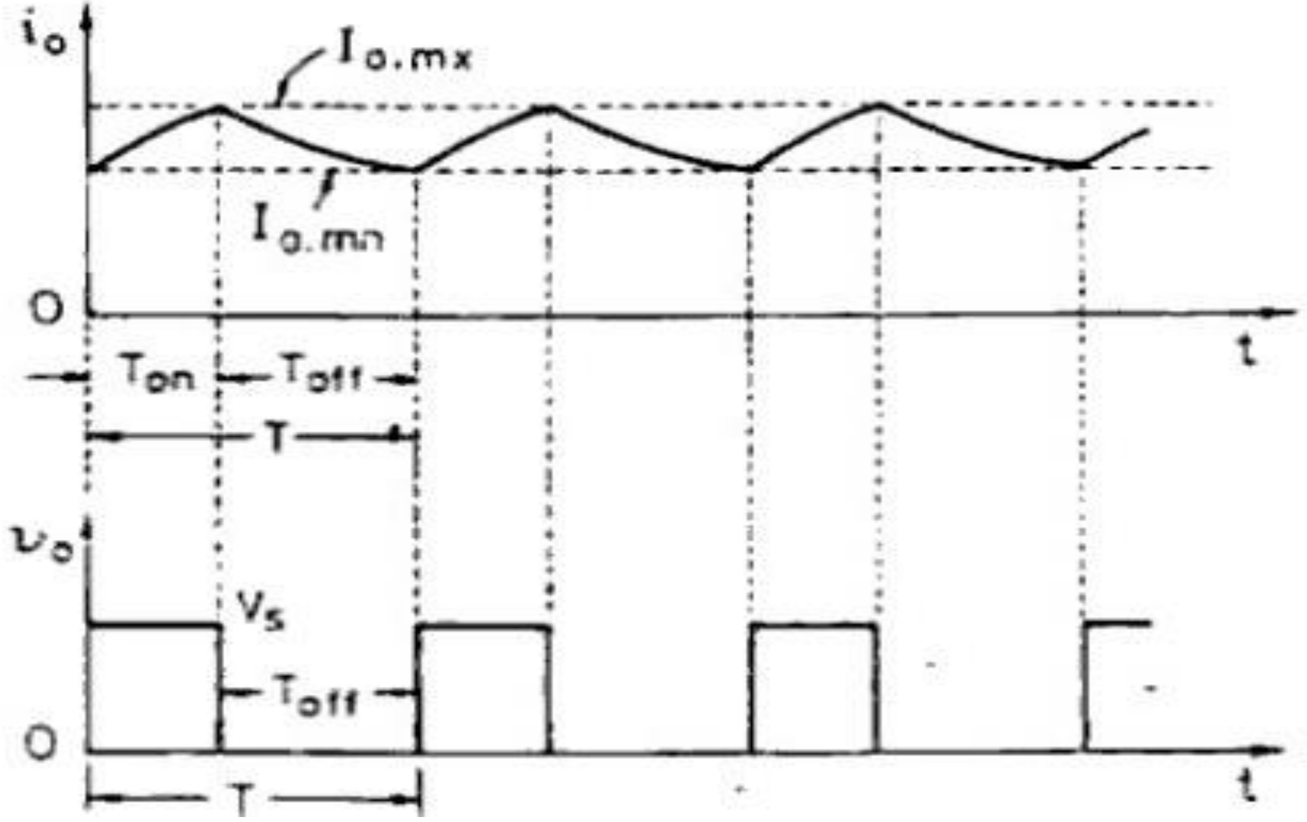
(b)

2. Variable frequency system – Here T is varied and T_{on} or T_{off} is kept constant. This method of control is called frequency modulation scheme. From fig (a) & (b) we can see that Ton is kept constant and T is varied to vary the output voltage.



b) Current limit control

- Here the On and Off of chopper circuit is guided by the previous set value load current
- When load current reaches the upper limit (I_{max}), chopper is switched off
- When load current falls to lower limit (I_{min}), chopper is switched ON.



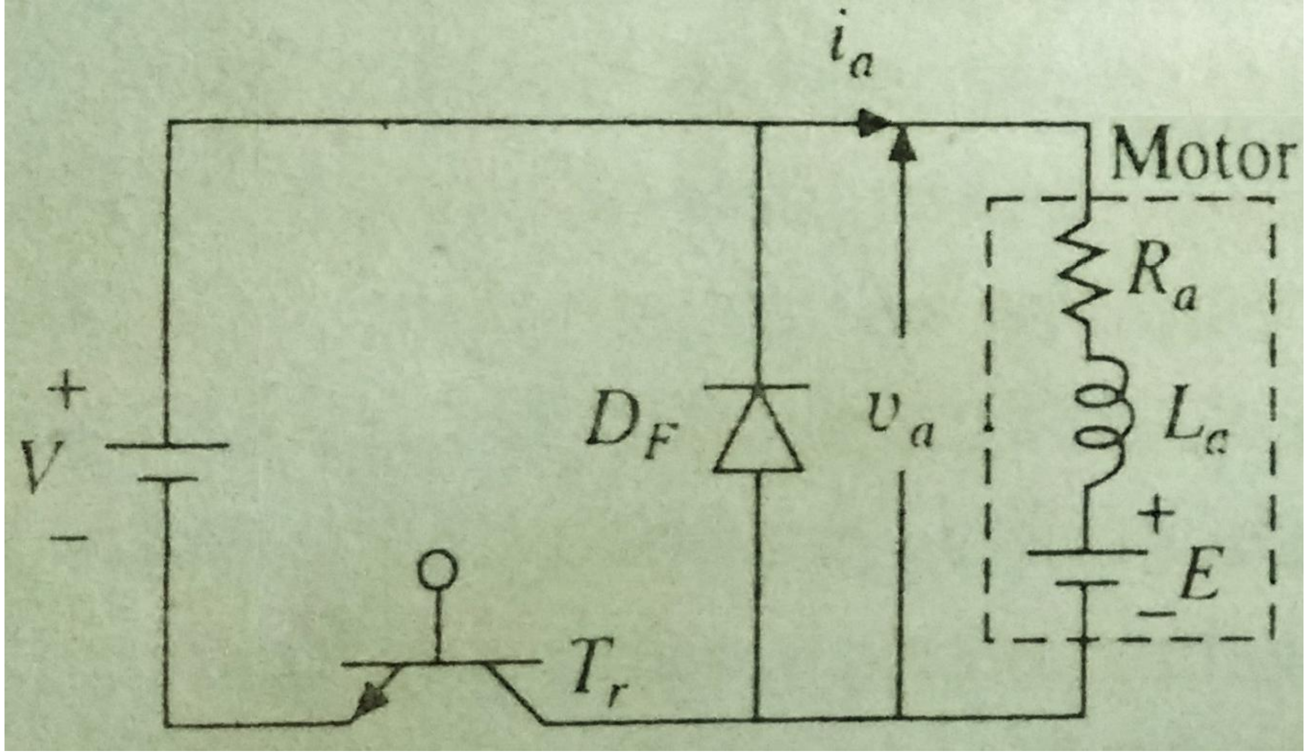
- There are single, two & four quadrant chopper fed DC drives

1. Single quadrant chopper fed separately excited DC motor drive

a. Ist quadrant chopper fed DC drive (Motoring control)

- A transistor chopper fed DC motor drive is shown in figure
- The transistor T_r is operated periodically with period T and remains ON for a duration T_{on}

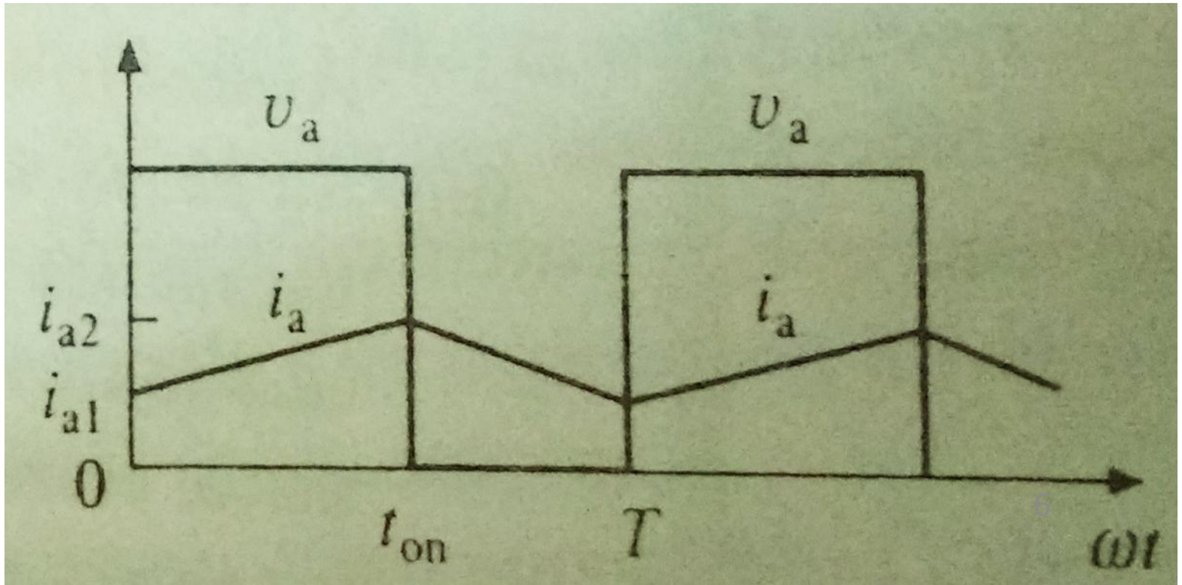
- During T_{on}, the motor terminal voltage is V
- i.e, $i_a R_a + L_a(di_a/dt) + E = V$, for $0 < t < t_{on}$ (Duty interval)
- In this interval, motor current increases from i_{a1} to i_{a2}



At $t = t_{on}$, T_r is turned OFF. Motor current freewheels through diode D_F & output voltage is zero (Free wheeling interval)

i. e, i.e, $i_a R_a + L_a(di_a/dt) + E = 0$,

for $_{on} < t <$



- In this interval, motor current decreases from i_{a2} to i_{a1}
- Duty ratio or duty cycle, $D = t_{on}/T$

- From output voltage waveform, average value of output voltage (voltage applied to armature),

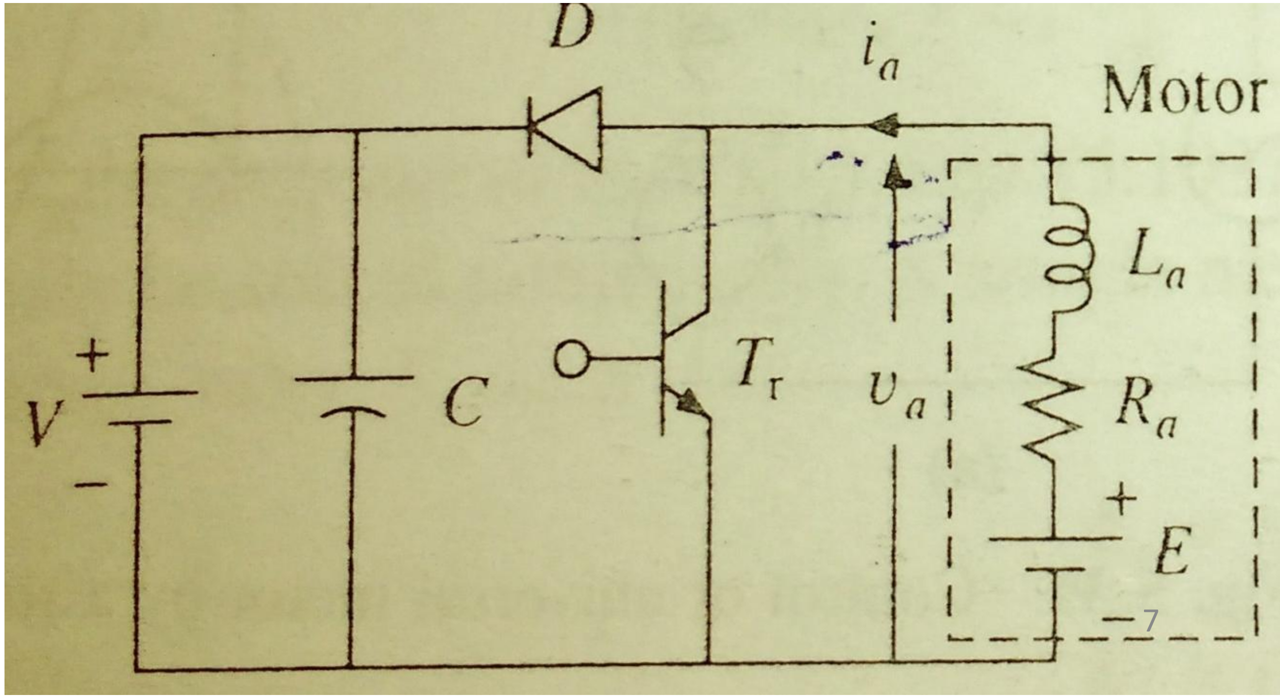
$$V_{avg} = \frac{1}{T}\int_0^{t_{on}} V\,dt = \frac{V}{T}\,t\Big]_0^{t_{on}} = V\,\frac{t_{on}}{T}$$

$$i.e, \quad V_{avg} = DV$$

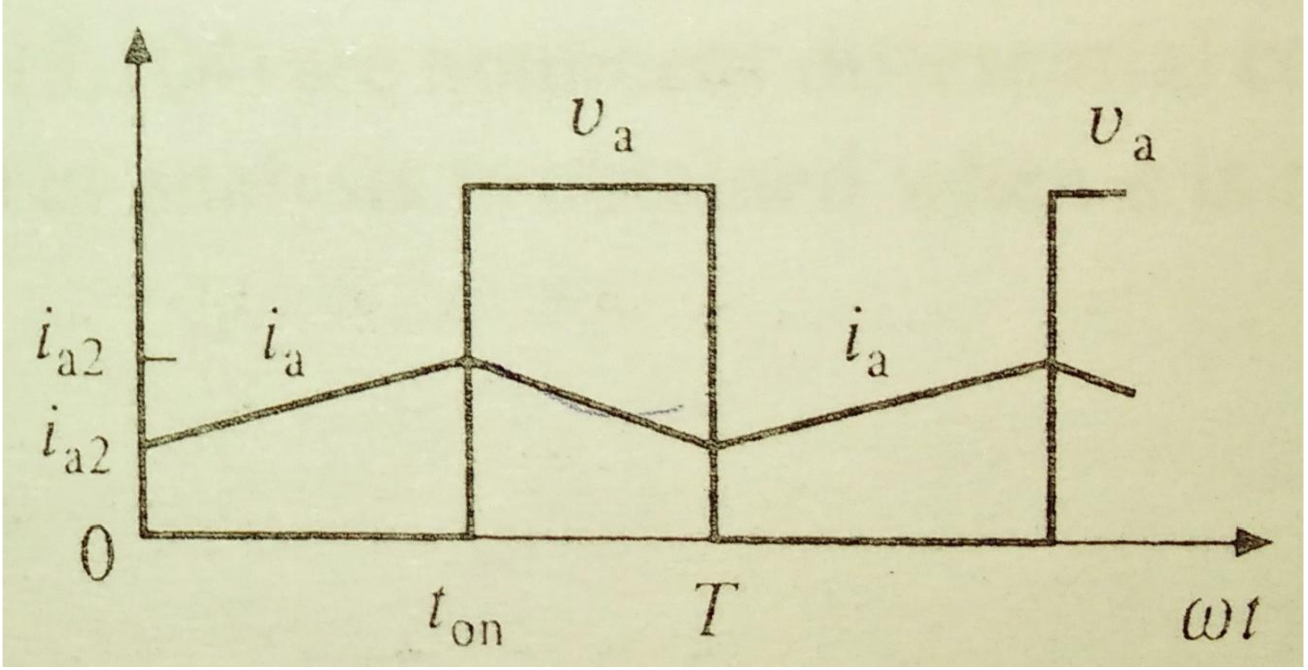
- From above equation, it is clear that by varying the duty cycle D, the chopper output voltage can be controlled & hence the speed of motor

b. <u>IInd quadrant chopper fed DC drive (Regenerative braking control)</u>

- Here energy from the motor is fed back to supply
- Here transistor T_r is operated periodically witn a period T
- On period of T_r = t_{on}



- When T_r is ON, motor current increases from i_{a1} to i_{a2}
- The motor is working as a generator converting mechanical energy to electrical energy

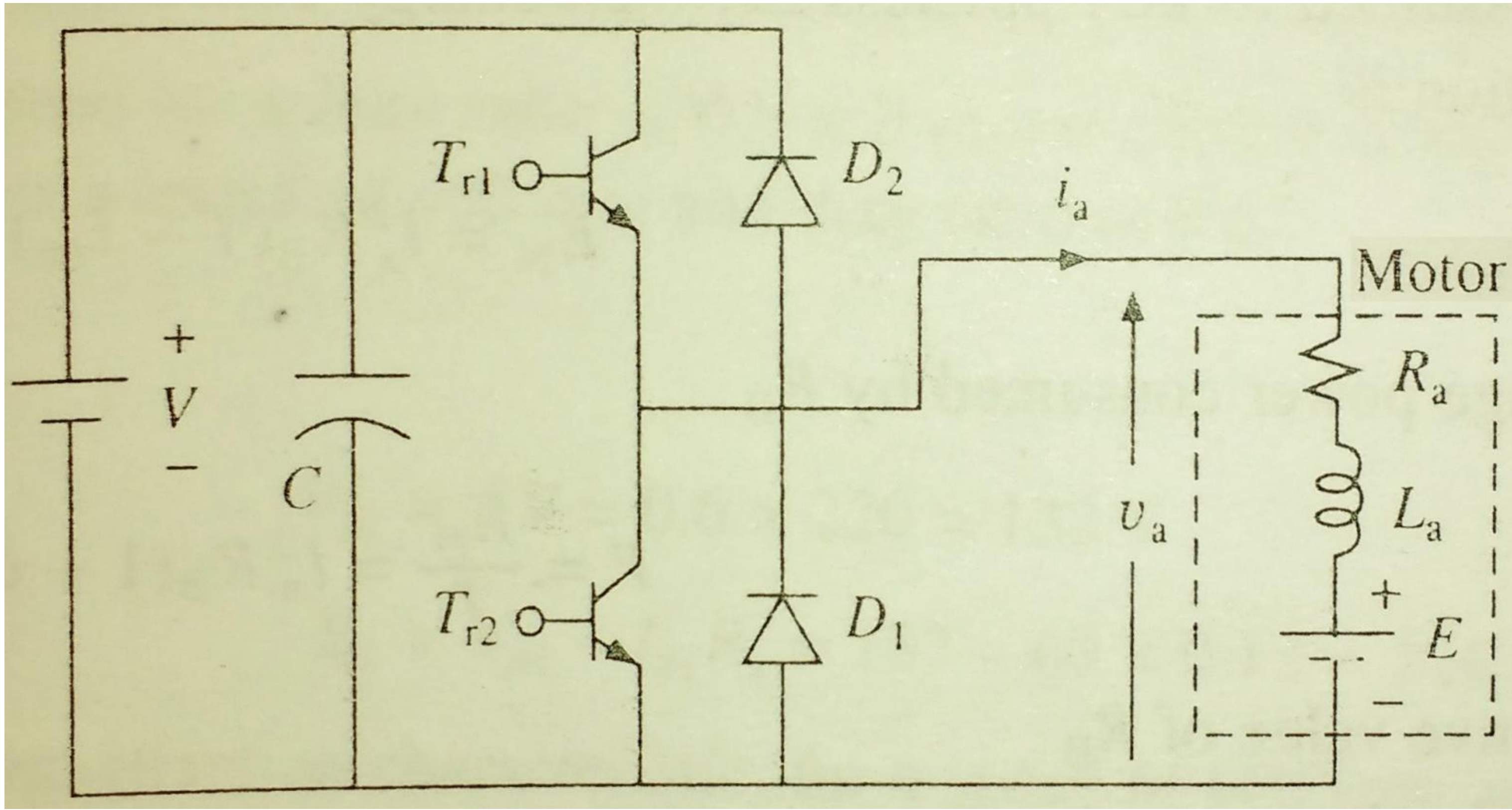


- When T_r is turned OFF, motor current flows through the diode D to source. Also current decreases from i_{a2} to i_{a1}
- The interval $0< t <t_{on}$ is called energy storage interval and the interval $t_{on}< t <T$ is called duty interval
- Duty ratio, $D = (T-t_{on})/T$
- From wave form, Average value of output voltage $V_{avg} = \frac{1}{T}\int_{t_{on}}^{T} V\,dt$

$$i.e, \quad V_{avg} = DV$$

2. Two quadrant chopper fed separately excited DC motor drive

- A two quadrant chopper can provide motoring & regenerative braking in forward direction
- Here Transistor T_{r1} & Diode D_1 form a chopper circuit & provide control for forward motoring operation
- Transistor T_{r2} & Diode D_2 form a chopper circuit & provide control for forward regenerative braking

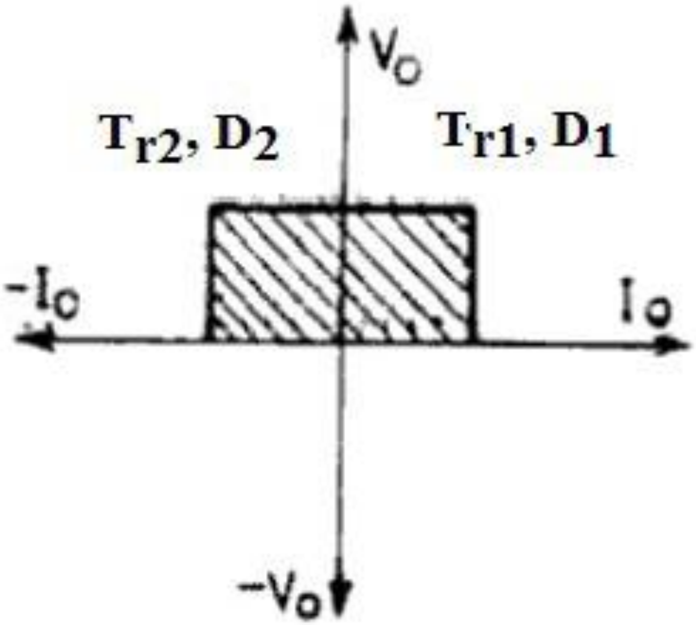


I^st quadrant operation

- If T_{r1} is ON with T_{r2} OFF, current flows from DC supply to load, voltage across the load is positive
- When T_{r1} is OFF, the motor current free wheels through diode D_1

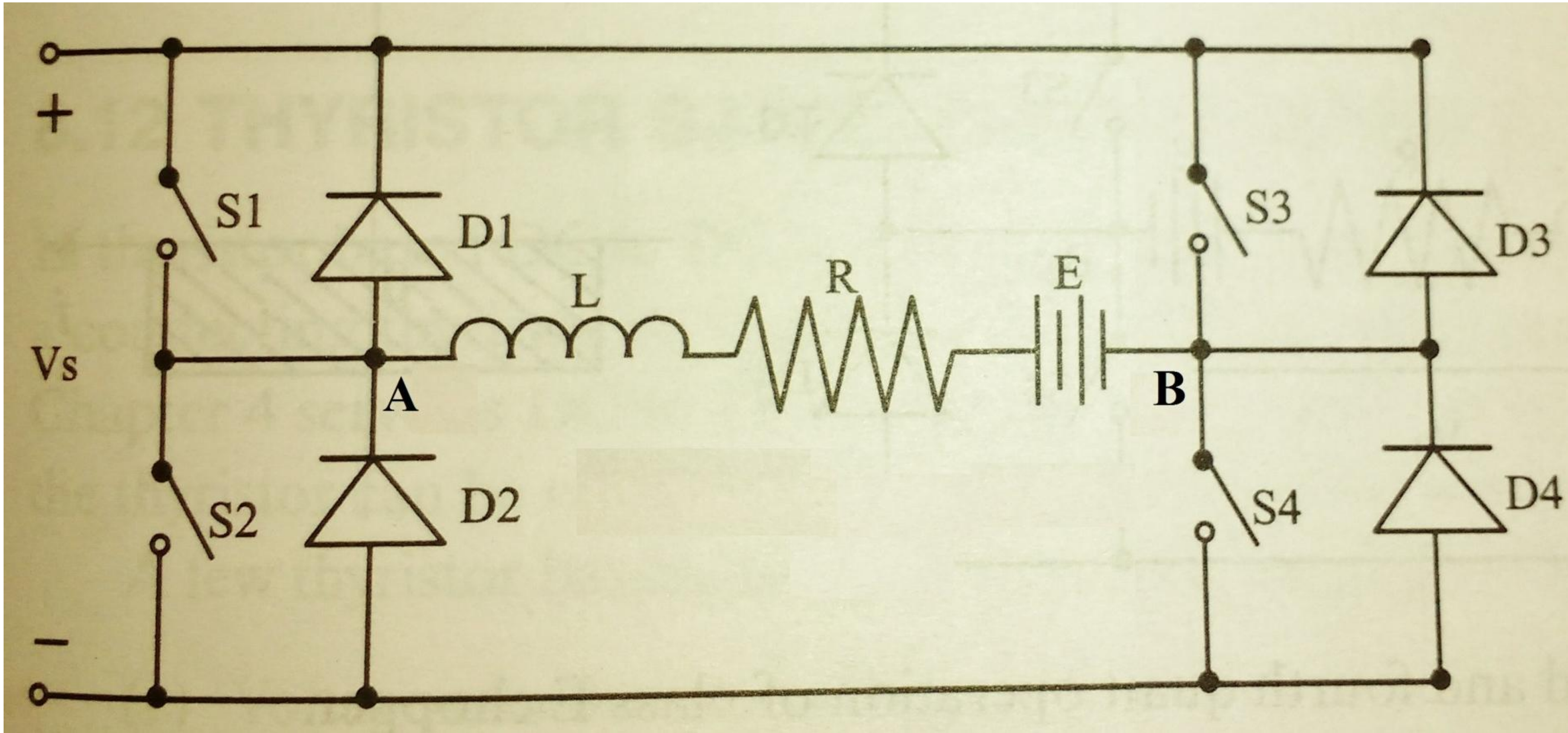
II^nd quadrant operation

- If T_{r2} is ON with T_{r1} OFF, motor works as generator, producing electrical energy & is stored in inductance
- When T_{r2} is OFF, energy stored in the circuit is released to supply through diode D_2



Four quadrant chopper fed separately excited DC motor drive

- A four quadrant chopper can provide motoring & regenerative braking in both forward & reverse direction
- The four quadrant chopper circuit is shown in figure
- It contain 4 transistors as switches & 4 diodes



- Here both load voltage & current can be either positive or negative
- Care must be taken to make sure that the switches S1 & S2 as well as switches S3 & S4 are not turned ON simultaneously, otherwise supply voltage will be short circuited

Quadrant I operation

- For this, Switch S1 is operated (turned ON & OFF), S4 is kept ON & all other switches are kept OFF
- When S1 is ON, the point A gets connected to positive terminal of DC supply and point B connected to negative terminal of supply through S4, the machine operates as a motor in forward direction
- When S1 is OFF, the current in the circuit decreases suddenly & inductor reverses its polarity. Now diode D2 turns ON & armature current freewheels through S4 & D2
- Thus we get Ist quadrant operation

Quadrant II operation

- For this, switch S2 is operated & all other switches are kept OFF
- When S2 is ON, Diode D4 is forward biased & armature current freewheels through S2 & D4. Now inductor stores energy

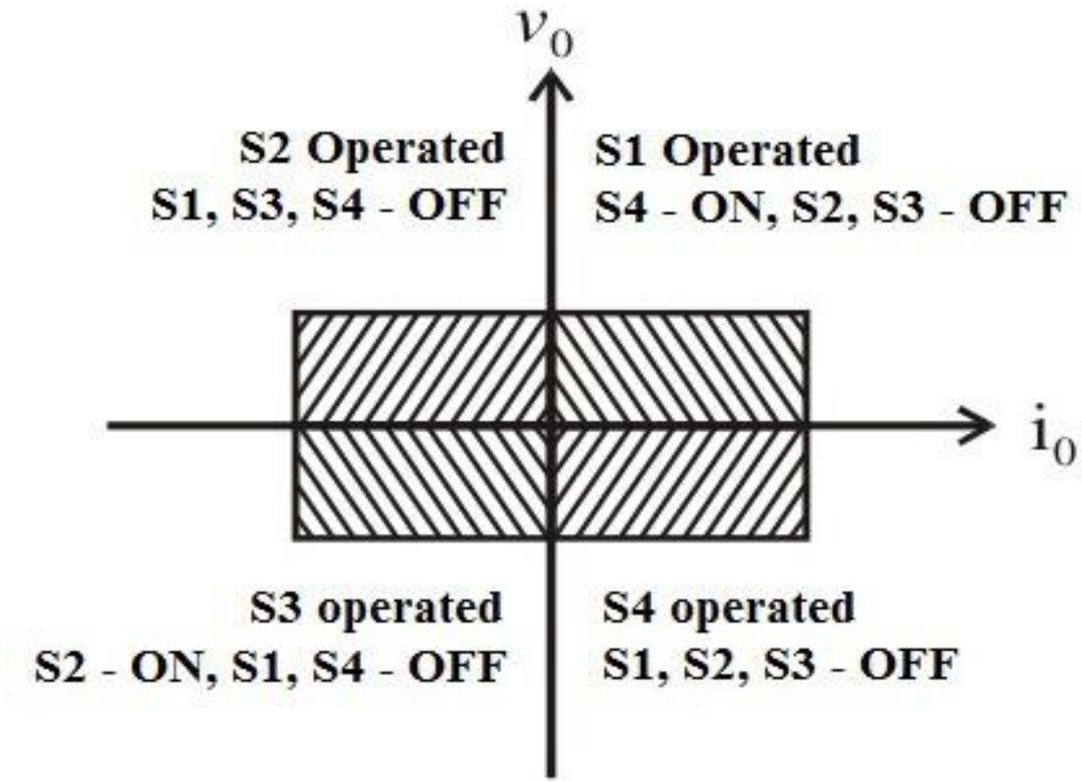
- When S2 is OFF, the current in the circuit decreases suddenly & inductor reverses its polarity. Now diode D1 turns ON & power flows from motor to source through D4 & D1 (the back emf & inductor voltage adds up to get a voltage higher than supply voltage, power flows from motor to source)
- i.e, machine operates in regenerative braking mode in forward direction

Quadrant III operation

- For this, Switch S3 is operated, S2 is kept ON & all other switches are kept OFF
- When S3 is ON, the point B gets connected to positive terminal of DC supply and point A connected to negative terminal of supply through S2, the machine operates as a motor in reverse direction (here the polarity of back emf reverses)
- When S3 is OFF, the current in the circuit decreases suddenly & inductor reverses its polarity. Now diode D4 turns ON & armature current freewheels through S2 & D4
- Thus we get IIIrd quadrant operation

Quadrant IV operation

- For this, switch S4 is operated & all other switches are kept OFF
- When S4 is ON, Diode D2 is forward biased & armature current freewheels through S4 & D2. Now inductor stores energy
- When S4 is OFF, the current in the circuit decreases suddenly & inductor reverses its polarity. Now diode D3 turns ON & power flows from motor to source through D2 & D3 (the back emf & inductor voltage adds up to get a voltage higher than supply voltage, power flows from motor to source)
- i.e, machine operates in regenerative braking mode in reverse direction



Cycloconverters

- A Cycloconverter is a power electronic circuit that converts fixed voltage & frequency AC supply into variable voltage & frequency AC
- Traditionally, AC to AC conversion is done in two different ways

1. In two stages (AC-DC & then DC-AC) as in DC link converters
2. In one stage (AC-AC) as in Cycloconverters

- There are different types of Cycloconverters

According to output frequency

1. Step up cycloconverter – here output frequency is greater than input frequency
2. Step down cycloconverter – here output frequency is less than input frequency

According to supply voltage

1. Single phase to single phase cycloconverter (Centre tapped & bridge configuration)
2. Three phase to three phase cycloconverter
3. Three phase to single phase cycloconverter

- Cycloconverters are used for high power applications
- Output voltage & frequency can be controlled
- Thyristors are used as switching devices

Applications

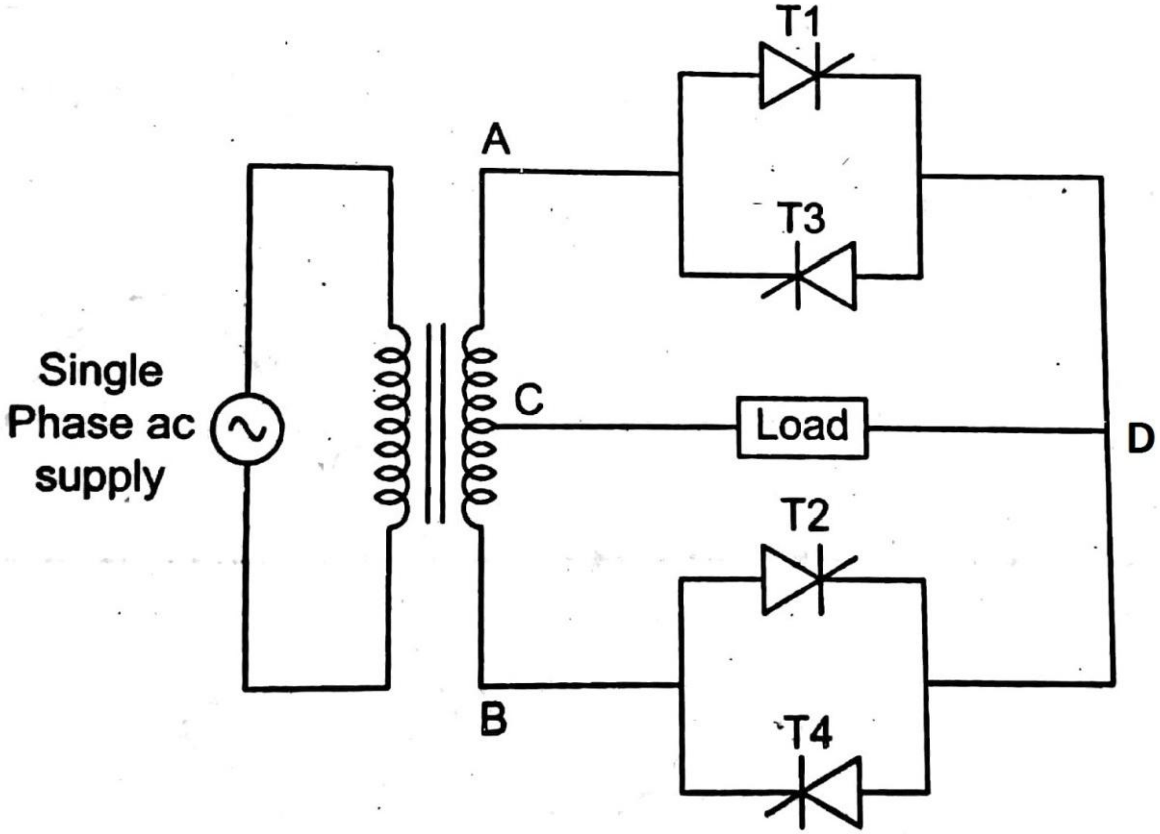
- Speed control of high power AC drives
- Induction heating
- Static VAR compensation

<u>1 phase to 1 phase Cycloconverter</u>

- Here input & output AC voltages are 1 phase
- This converter can work as a step up/ step down cycloconverter
- Two configurations are possible

1. Mid point/Centre tapped type cycloconverter

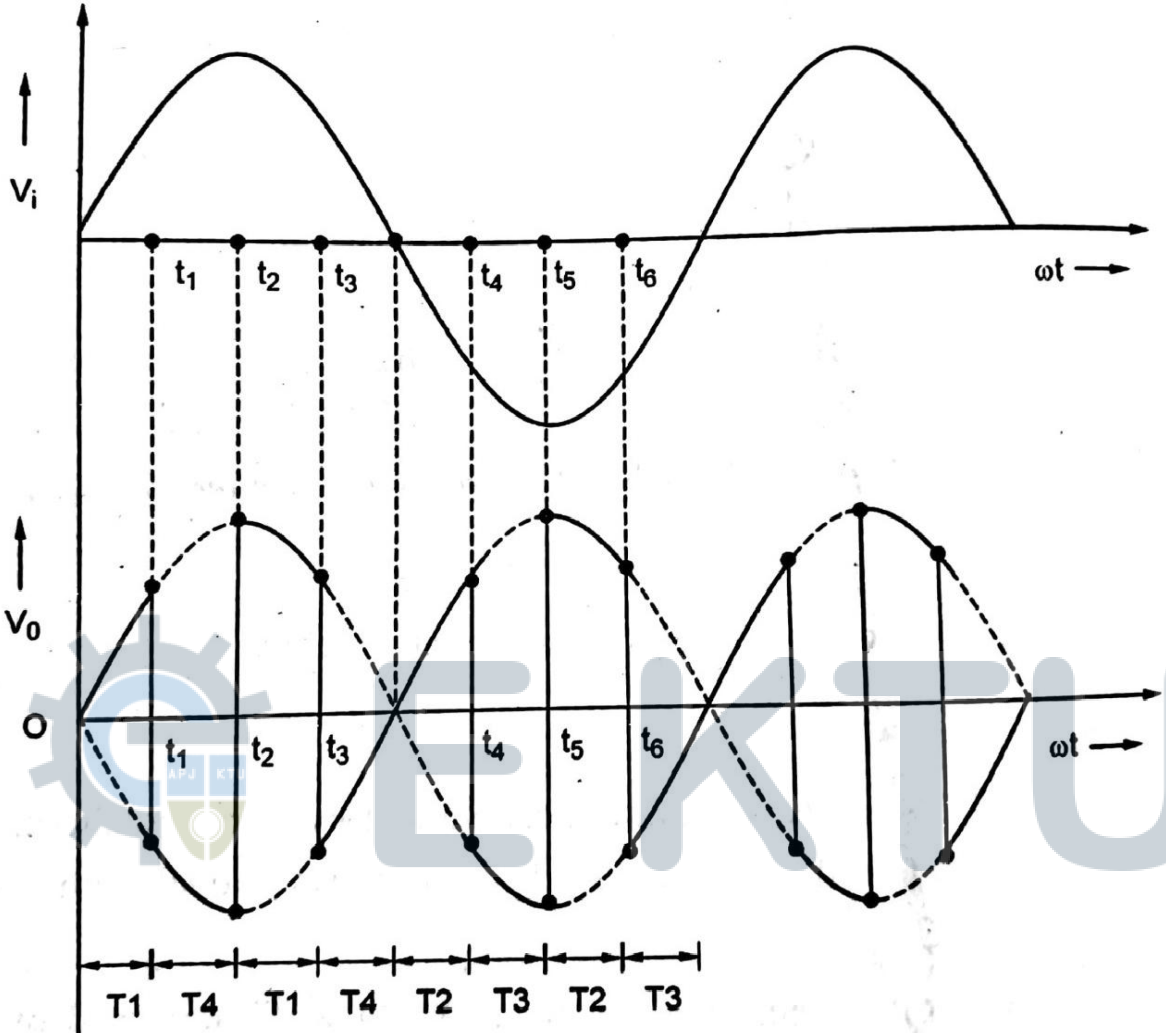
- A mid point type cycloconverter configuration is shown in fig.
- There are two groups of SCRs – positive group (T1 & T2) & negative group (T3 &T4)



Step up cycloconverter operation

- SCR T1 is turned ON during positive half cycle of supply at time t=0, therefore load current flows through path A-T1-D-Load-C
- Output voltage is positive during this time
- At t=t1, SCR T1 is force commutated & T4 is turned ON. Now load current flows through path C-Load-D-T4-B
- Out put voltage is negative this time.

- At t=t2, T4 is force commutated & T1 is turned ON
- Now output voltage become positive again
- At t=t3, T1 is force commutated again & T4 is turned On
- As a result output voltage become negative
- At π SCR T2 is turned ON. Now load current flows through B-T2-D-Load-C
- The output voltage become positive
- At t=t4, T2 is turned OFF by force commutation & T3 is turned ON
- The output voltage become negative
- At t=t5, T3 is force commutated & T2 is turned ON
- The output voltage become positive again
- At t=t6, T2 is turned OFF by force commutation & T3 is turned ON
- The output voltage become negative
- Here the output frequency is 4 times input frequency

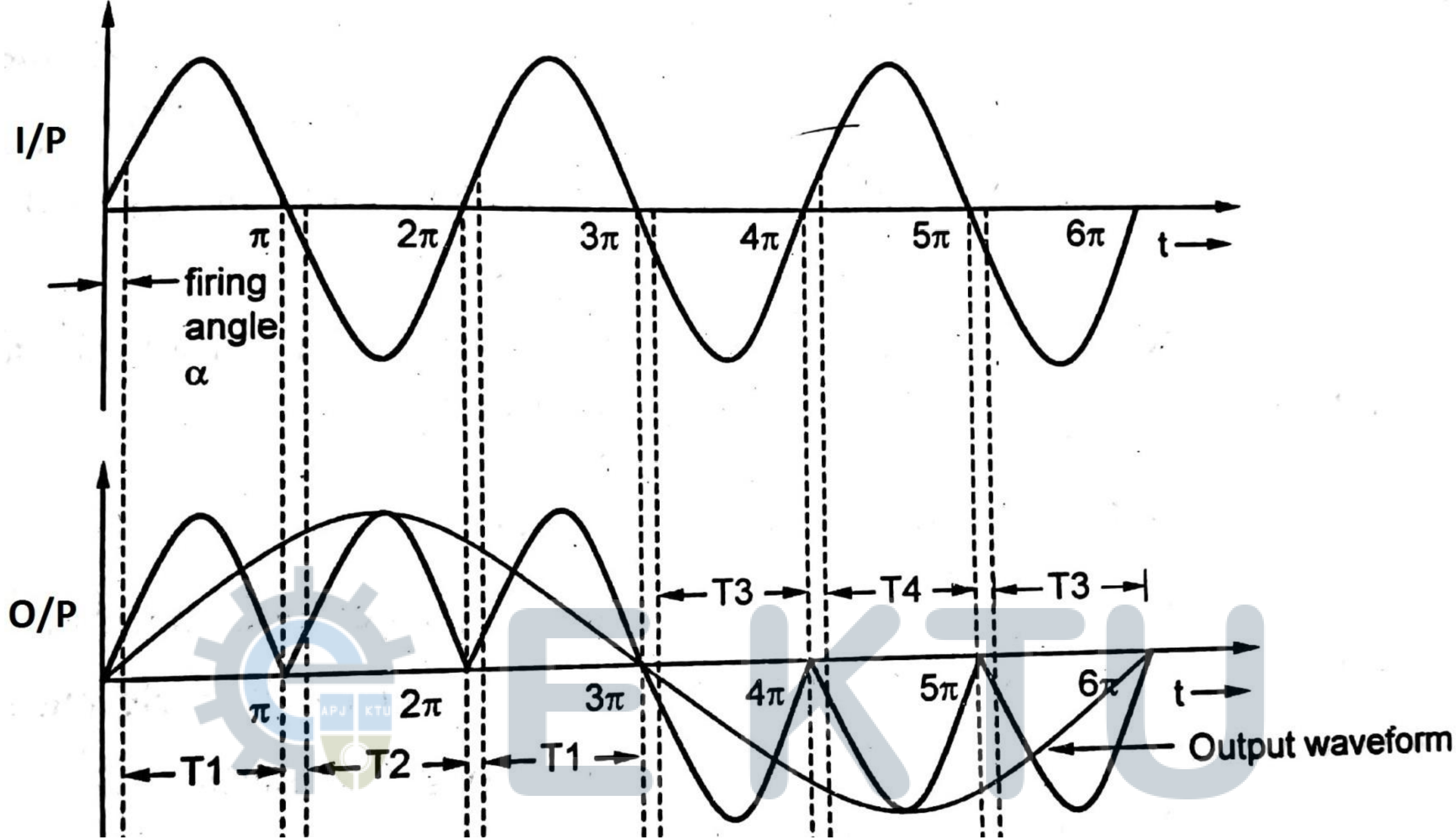


Step down cycloconverter operation

- During positive half cycle of supply, at t=0 SCR T1 is turned ON
- Now load current flows through A-T1-D-Load-C
- At π, T1 gets naturally commutated and T2 is turned ON

- Now load current flows through B-T2-D-Load-C
- At 2π, T2 gets naturally commutated & T1 is turned ON again
- Now load current flows through A-T1-D-Load-C
- At 3π, T1 gets naturally commutated & T3 is turned ON
- Now load current flows through C-Load-D-T3-A
- At 4π, T3 gets naturally commutated & T4 is turned ON
- Now load current flows through C-Load-D-T4-B
- At 5π, T4 gets naturally commutated & T3 is turned ON
- Now load current flows through C-Load-D-T3-A
- here the output frequency is (1/3) times Input frequency
- The waveforms are shown in next slide

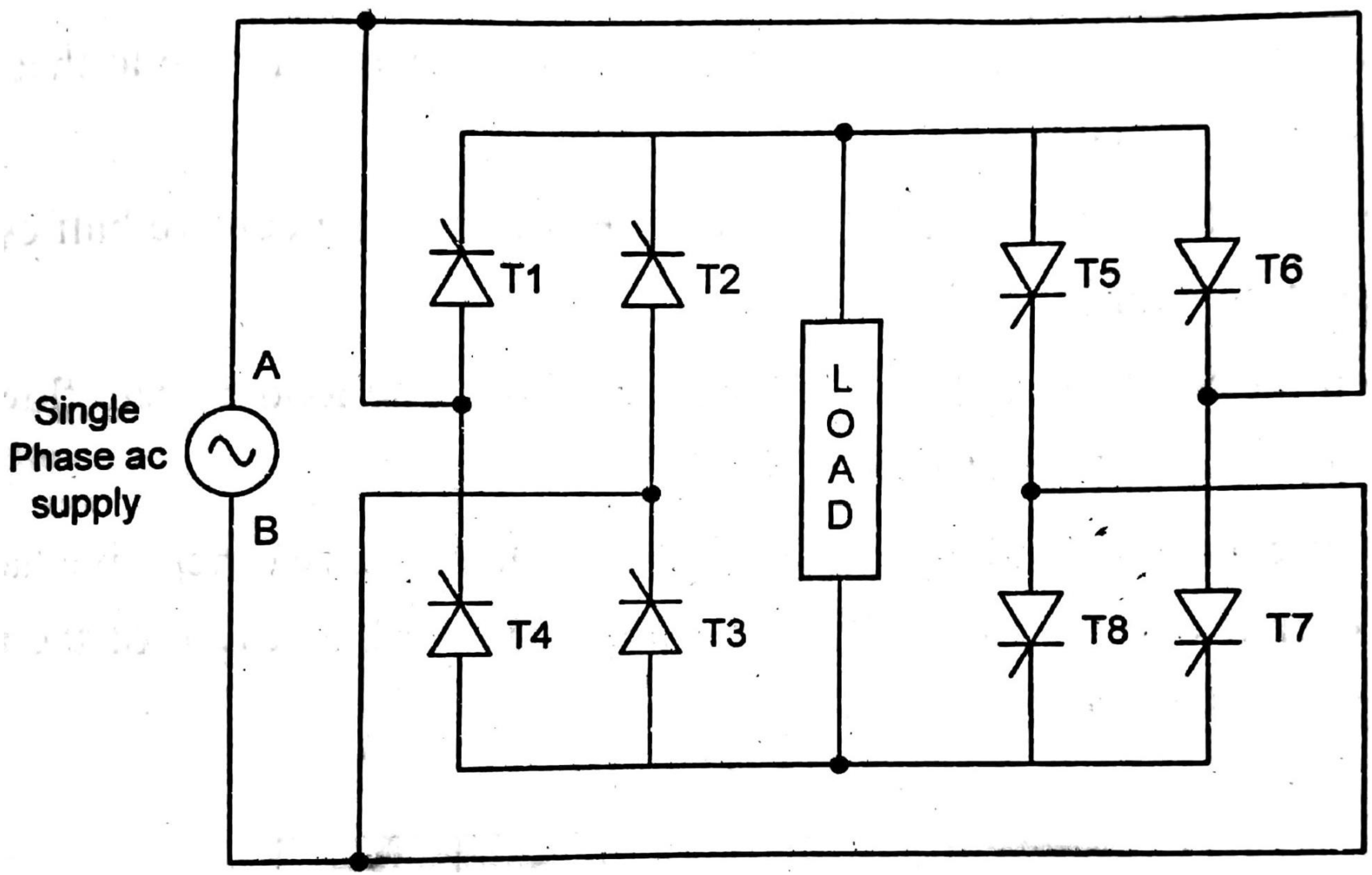
- ***Here the output voltage can be adjusted by varying the firing angle of thyristors***



2. <u>1 phase bridge type cycloconverter</u>

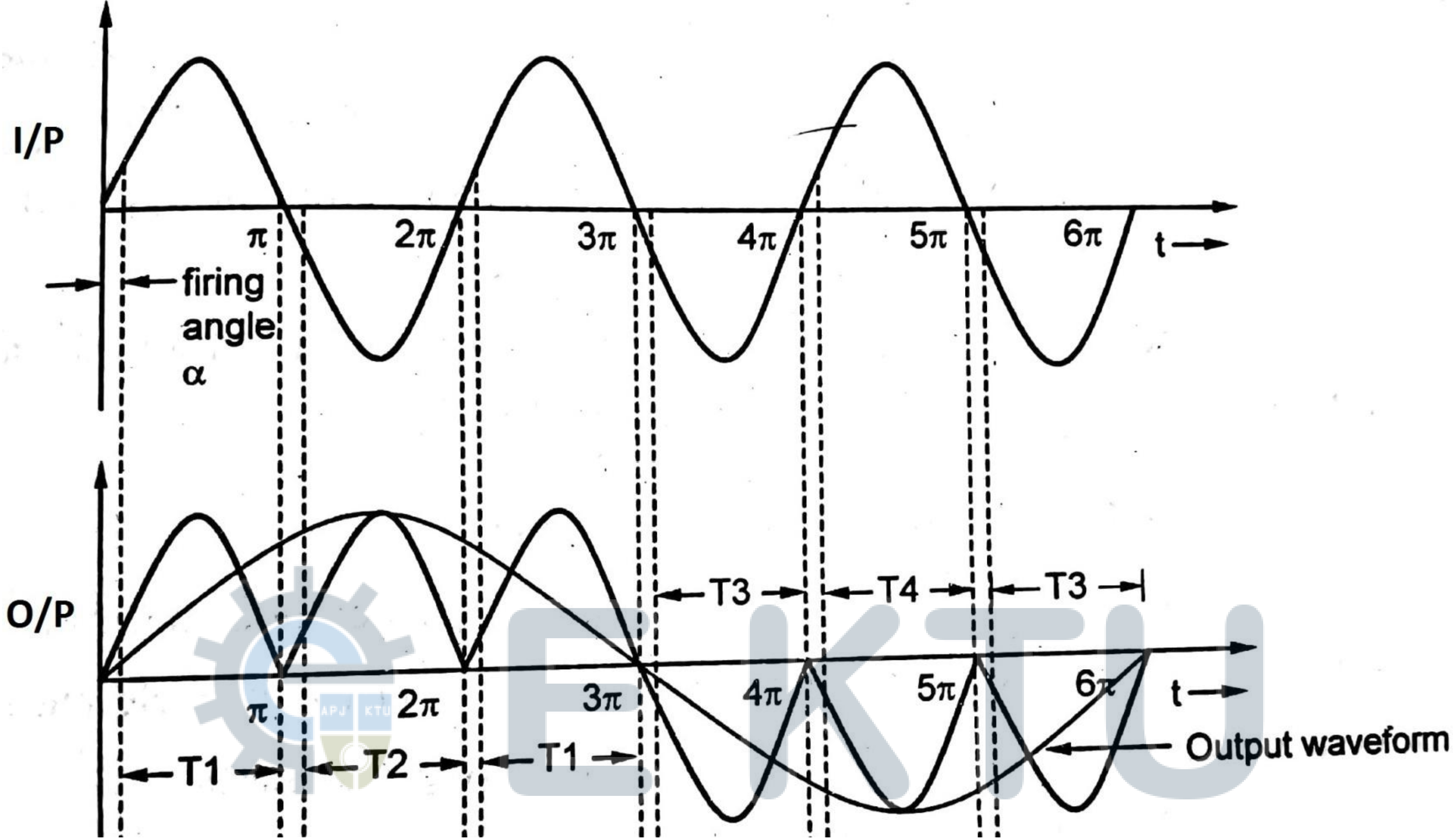
- Here transformer with tapping not required
- Circuit configuration is shown in next slide
- The SCR T1 to T4 works as positive group & SCR T5 to T8 works as negative group.

- If Positive group & negative group thyristors conduct simultaneously, the supply is short circuited & it should be avoided
- It can work as a step up/down cycloconverter



Step down Cycloconverter operation

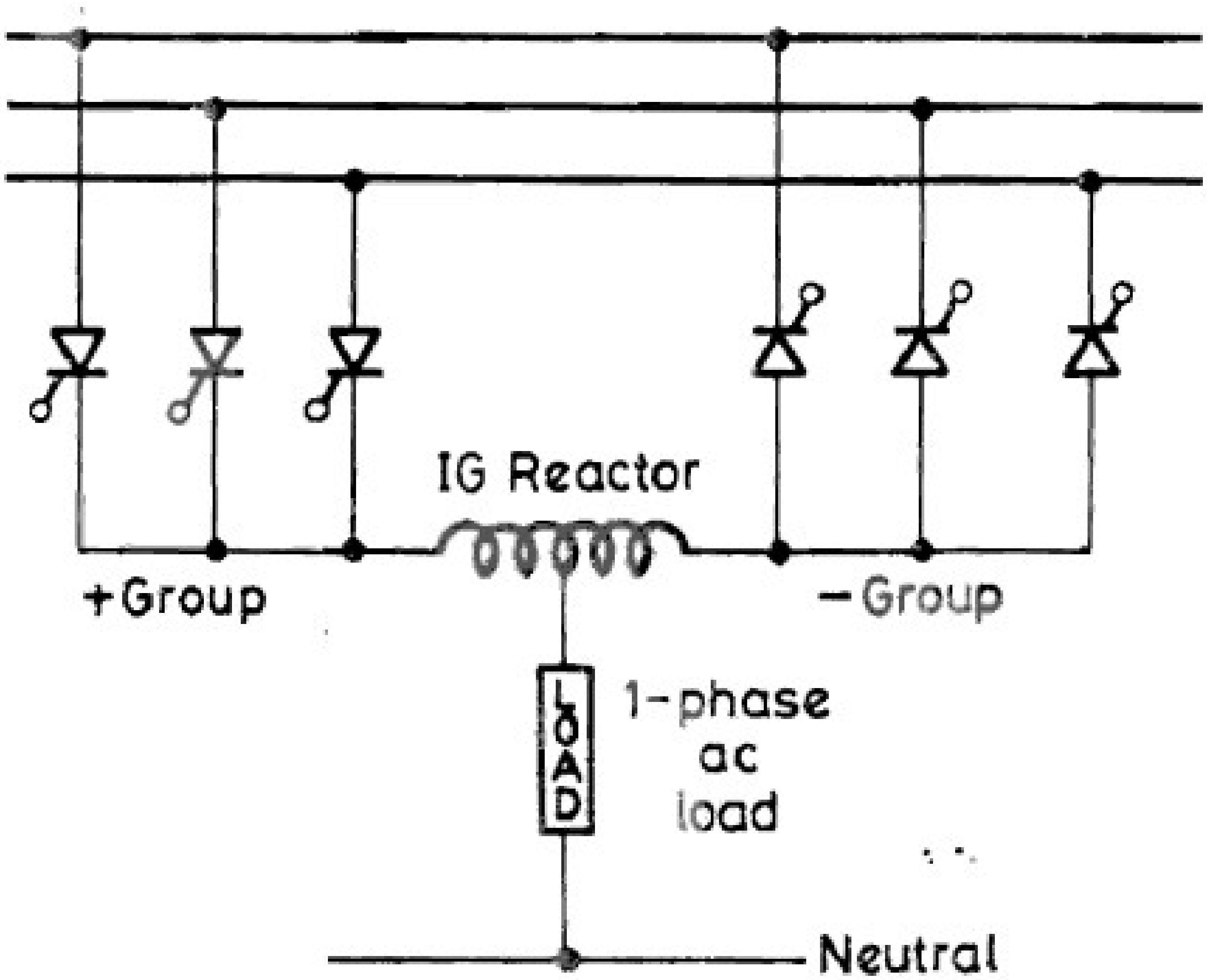
- During positive half cycle of supply at t=0, T1 & T3 are turned ON & load current flows through the path A-T1-Load-T3-B
- At π, T1 & T3 get naturally commutated & T2 & T4 are turned ON
- Now load current flows through the path B-T2-Load-T4-A
- At 2π, T2 & T4 get naturally commutated and T1 & T3 are turned ON
- Now load current flows through the path A-T1-Load-T3-B
- At 3π, T1 & T3 gets naturally commutated
- Now T6 & T8 are turned ON, load current flows through the path B-T8-Load-T6-A
- At 4π, T6 & T8 gets naturally commutated and T5 & T7 are turned ON
- Load current flows through the path A-T7-Load-T5-B
- At 5π, T5 & T7 gets naturally commutated
- Now T6 & T8 are turned ON, load current flows through the path B-T8-Load-T6-A



I/P
π
2π
3π
4π
5π
6π
t
firing angle α
O/P
π
2π
3π
4π
5π
6π
t
T1
T2
T1
T3
T4
T3
Output waveform

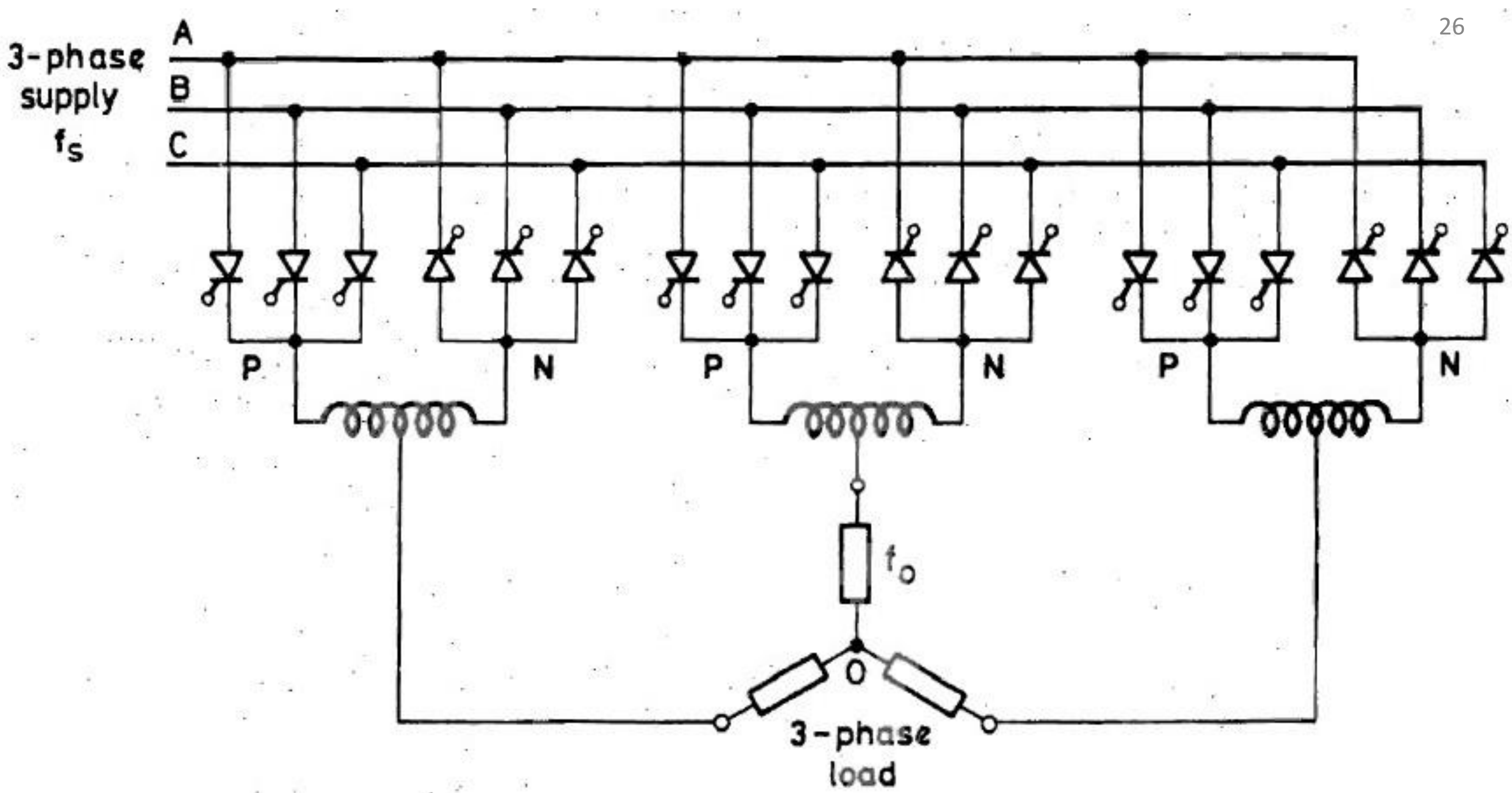
3 phase to 1 phase cycloconverter

- 3 phase to 1 phase cycloconverter is shown in figure
- Inter Group (IG) reactor is used to limit the circulating current between positive & negative group of thyristors



3 phase to 3 phase cycloconverter

- A 3 phase to 3 phase cycloconverter is shown in figure



Cycloconverter for Drive applications

- By using a cycloconverter, a variable voltage variable frequency AC supply can be obtained
- By feeding an Induction motor or synchronous motor from this supply, the speed can be controlled by v/f control method
- The harmonic content in the output of cycloconverter increases with increase in frequency
- Therefore the maximum output frequency is limited to 40% of source frequency
- As a result the maximum speed is limited to 40% of synchronous speed at mains frequency
- This drive has regenerative braking capability
- Since cycloconverter uses large number of thyristors, it become economically acceptable only in large power drives
- Cycloconverters are used in high power drives requiring good dynamic response but only low speed operation. Eg-ball mill in a cement plant

Speed Control of Induction Motor

There is a various method of speed control of an Induction Motor. The rotor speed of an induction motor is given by the equation shown below. From the equation (1) it is clear that the motor speed can be changed by a change in frequency f, a number of poles P, and slip s.

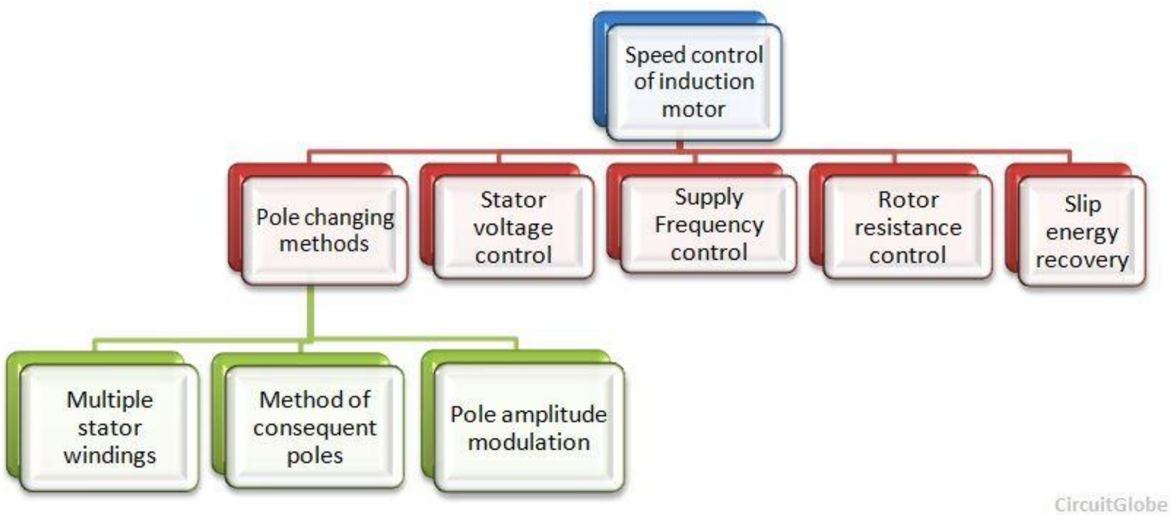
$$N_r = (1 - s)\,N_s \quad \text{and}$$

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

Therefore,

$$N_r = \frac{120f}{P}(1 - s) \quad \ldots\ldots (1)$$

Any one or combinations of the above methods listed can be used to change the motor speed. All the methods of speed control of an induction motor are used in actual practice.



(I) Pole Changing Method

Pole Changing Method is one of the main methods of the speed control of an induction motor. This method of controlling the speed by pole changing is used mainly for cage motor only because the cage rotor automatically develops a number of poles, which is equal to the poles of the stator winding. The number of stator poles can be changed by the following three methods. They are known as multiple stator windings, method of consequent poles and pole amplitude modulation (PAM).

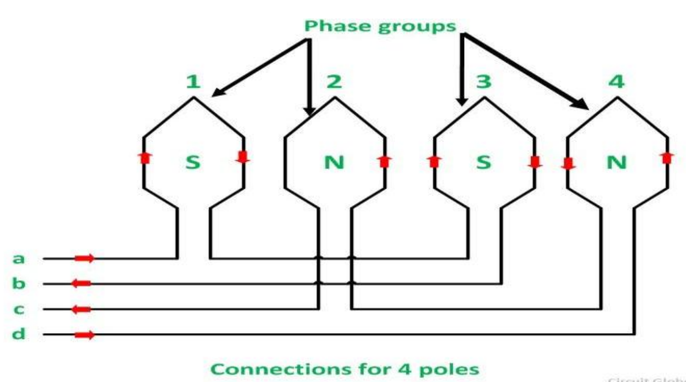
(a) Multiple Stator Winding

In the multiple stator winding method, two windings are provided on the stator which are wound on the two different numbers of pole. One winding is energized one at a time. Let us consider that the motor has two windings for 6 and 4 poles. For the frequency of 50 hertz, the synchronous speeds will be 1000 and 1500 revolutions per minute respectively. This method of speed control is less efficient and more costly.

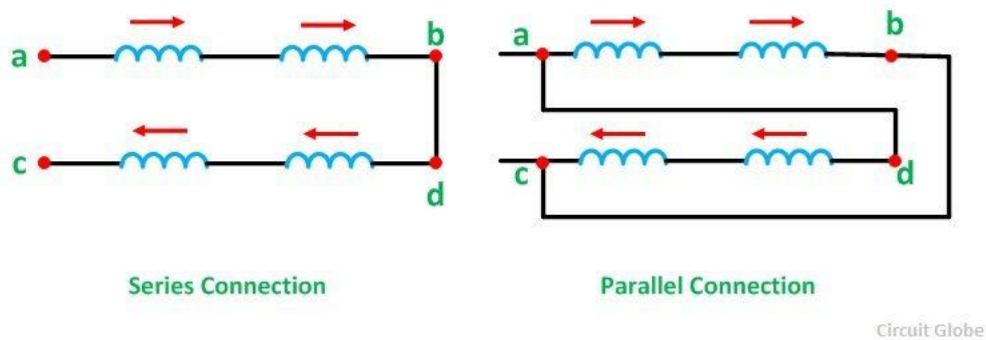
(b) Method of Consequent Pole

In the method of consequent poles, a single stator winding is divided into few coil groups. The terminals of all these groups are brought out. By simply changing the coil connections, the number of poles can be changed. In practice, the stator windings are divided only in two coil groups. The number of poles can be changed in the ratio of 2:1.

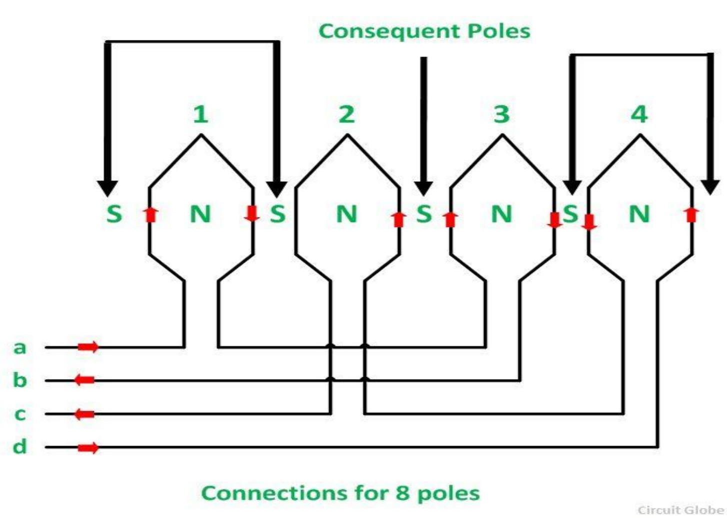
The figure below shows the single phase of a stator winding which consist of 4 coils. The coils are divided into two groups named as a-b and c-d.



Group a-b consists of an odd number of coils that is (1, 3) whereas group c-d consists of an even number of coils (2,4). The two coils are connected in series. The terminals a, b, c, d are taken out as shown in the above figure. The coils are carrying current in the given directions by connecting coil groups either in series or in parallel as shown in the figure below.



There are total four poles which are giving a speed of 1500 rpm for a 50-hertz system. If the current through the coils of group a-b is reversed as shown in the figure below. All the coils will produce north (N) poles.



The flux of the poles group should be passed through the given space between the pole group to complete the magnetic path. Thus, a magnetic pole of opposite polarity (S pole) is induced. These induced poles are known as Consequent Poles. Thus, the machine has twice as many poles as before (i.e., 8 poles), and the synchronous speed becomes half of the previous speed (i.e., 750 rpm).

The above principle can be extended to all the three phases of an induction motor. By choosing a combination of series and parallel connections between the coil groups of each phase. Also, the star or delta connections between the phase speed change can be obtained with constant torque and constant power operation or variable torque operation.

(c) Pole Amplitude Modulation (PAM) Technique

Pole amplitude modulation is a flexible method of pole changing which can be used in applications where speed ratios other than 2:1 are required. The motors designed for speed changing based on the poled amplitude modulation scheme are known as PAM motors.

II. Stator Voltage Control of an Induction Motor

Stator voltage control is basically a method to control the speed of an induction motor.

Initially, when the motor is started, heavy current flows through the field winding of the stator because back emf has not yet been induced. This heavy current can damage the coils of the motor. To avoid this, voltage of the stator is reduced.

The torque produced by running three phase induction motor is given by

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

In low slip region (sX_2) is very very small as compared to R_2. So, it can be neglected. So torque becomes

$$T \propto \frac{sE_2^2}{R_2}$$

Since rotor resistance, R_2 is constant so the equation of torque further reduces to

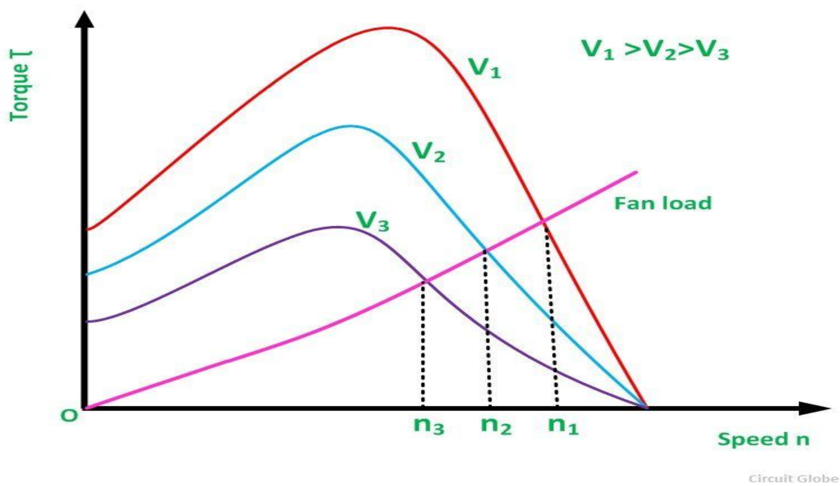
$$T \propto sE_2^2$$

We know that rotor induced emf $E_2 \propto V$. So, $T \propto sV_2$.

From the equation above it is clear that if we decrease supply voltage torque will also decrease and hence speed will decrease.

Stator Voltage Control is a method used to control the speed of an Induction Motor. The speed of a three phase induction motor can be varied by varying the supply voltage. As we already know that the torque developed is proportional to the square of the supply voltage and the slip at the maximum torque is independent of the supply voltage. The variation in the supply voltage does not alter the synchronous speed of the motor.

The **Torque-Speed Characteristics** of the three phase Induction motors for varying supply voltage and also for the fan load are shown below.



By varying the supplying voltage, the speed can be controlled.

The voltage is varied until the torque required by the load is developed, at the desired speed.

The torque developed is proportional to the square of the supply voltage and the current is proportional to the voltage.

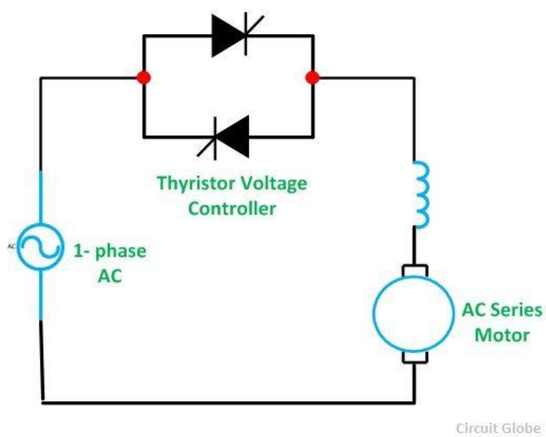
Hence, to reduce the speed for the same value of the same current, the value of the voltage is reduced and as a result, the torque developed by the motor is reduced. This stator voltage control method is suitable for the applications where the load torque decreases with the speed. For example- In the fan load.

This method gives a speed control only below the normal rated speed as the operation of the voltages if higher than the rated voltage is not admissible. This method is suitable where the intermittent operation of the drive is required and also for the fan and pump drives. As in fan and pump the load torque varies as the square of the speed. These types of drives required low torque at lower speeds. This condition can be obtained by applying lower voltage without exceeding the motor current.

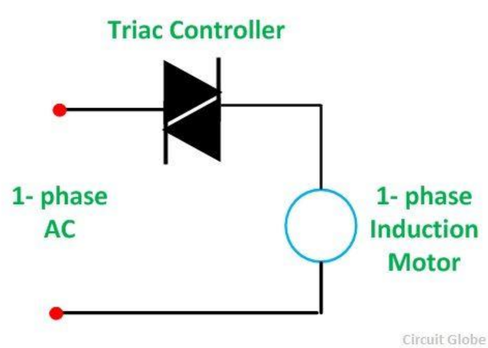
The variable voltage for speed control of small size motors mainly for single phase can be obtained by the following methods given below.

- By connecting an external resistance in the stator circuit of the motor.
- By using an Auto transformer.
- **By using a Thyristor voltage controller**
- **By using a Triac Controller**

Nowadays the Thyristor voltage controller method is preferred for varying the voltage. For a single phase supply, two Thyristors are connected back to back as shown in the figure below.

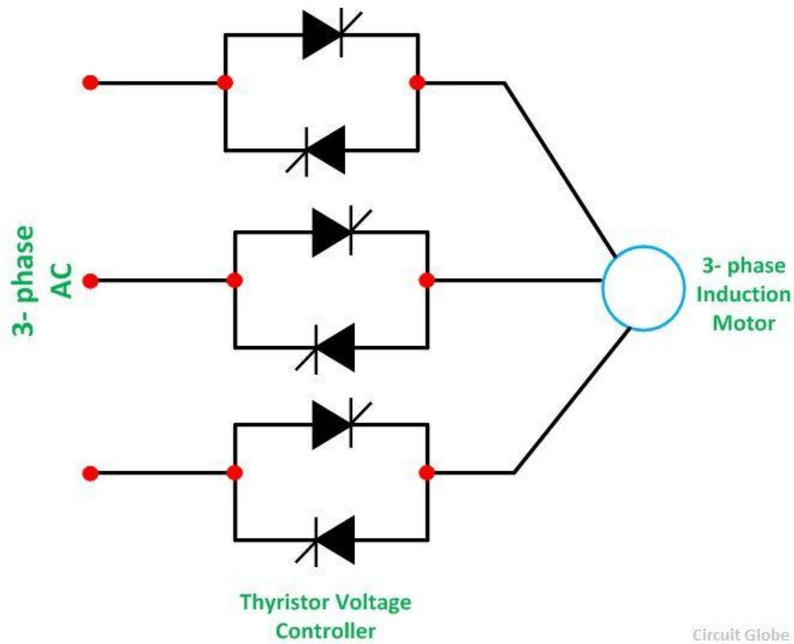


The domestic fan motors, which are single phase are controlled by a single phase Triac Voltage Controller as shown in the figure below.



Speed control is obtained by varying the firing angle of the Triac. ***These controllers are known as Solid State fan regulators***. As the solid state regulators are more compact and efficient as compared to the conventional variable resistance regulator. Thus, they are preferred over the normal regulator.

In case of a three phase induction, motor three pairs of Thyristor are required which are connected back to back. Each pair consists of two Thyristor. The diagram below shows the Stator Voltage Control of the three phase induction motors by Thyristor Voltage Controller.



Each pair of the Thyristor controls the voltage of the phase to which it is connected. Speed control is obtained by varying the conduction period of the Thyristor. For lower power ratings, the back to back Thyristor pairs connected in each phase is replaced by Traic.

III. Speed Control of Induction Motor by Stator Frequency Control

Variable Frequency Control is a method which is used to control the speed of an induction motor. The synchronous speed and therefore, the speed of the motor can be controlled by varying the supply frequency. The synchronous speed of an induction motor is given by the relation shown below.

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

The EMF induced in the stator of the induction motor is given by the equation shown below.

$$E_1 = 4.44 k_{w1} f \varphi T_1$$

Therefore, if the supply frequency is changed induced EMF will also change to maintain the same air gap flux. The terminal voltage V_1 is equal to the induced EMF E_1 if the stator voltage drop is neglected.

In order to minimise the losses and to avoid the saturation, the motor is operated at rated air gap flux. This condition is obtained by varying the terminal voltage with frequency so as to maintain (V/f) ratio constant at the rate value. This type of control is known as Constant Volts Per Hertz.

Thus, the speed control of an induction motor using variable frequency supply requires a variable voltage power source. The variable frequency supply is obtained by the following converters.

- Voltage source inverter
- Current source inverter
- Cyclo converter

An inverter converts a fixed voltage DC to a fixed or variable voltage AC with variable frequency. Cyclo converter converts a fixed voltage and fixed frequency AC to a variable voltage and variable AC frequency.

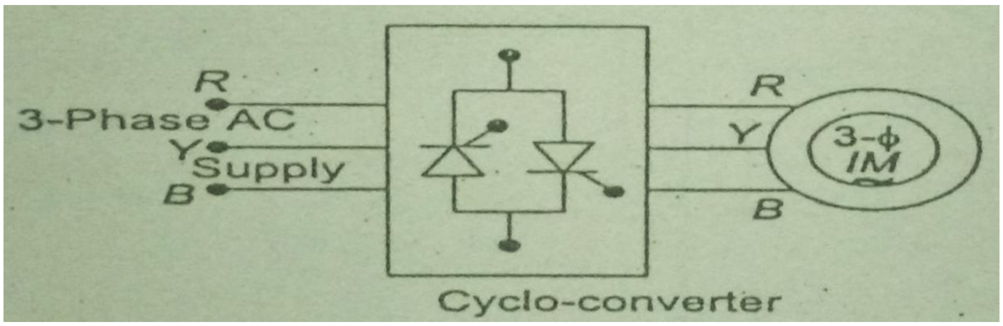
The variable frequency control allows good running and transient performance to be obtained from a cage induction motor. Cyclo converter controlled induction motor drive is suitable only for large power drives and to get lower speeds.

(a) Cycloconverters

- Converts AC supply frequency to a variable frequency

- When operating at low frequencies, output has low harmonic content

- Harmonic content increases with frequency making it necessary to limit the output frequency to 40% of source frequency
- Maximum speed is restricted to 40% of synchronous speed
- This will provide a smaller range of frequency variation, which is suitable for low speed, large power applications like ball mills, cement kiln etc
- The drive has regenerative braking capability
- 4 quadrant operation is obtained by reversing the phase sequence of motor terminal voltage



(b)Inverters

-It include rectification & inversion of supply

-It can be of two type

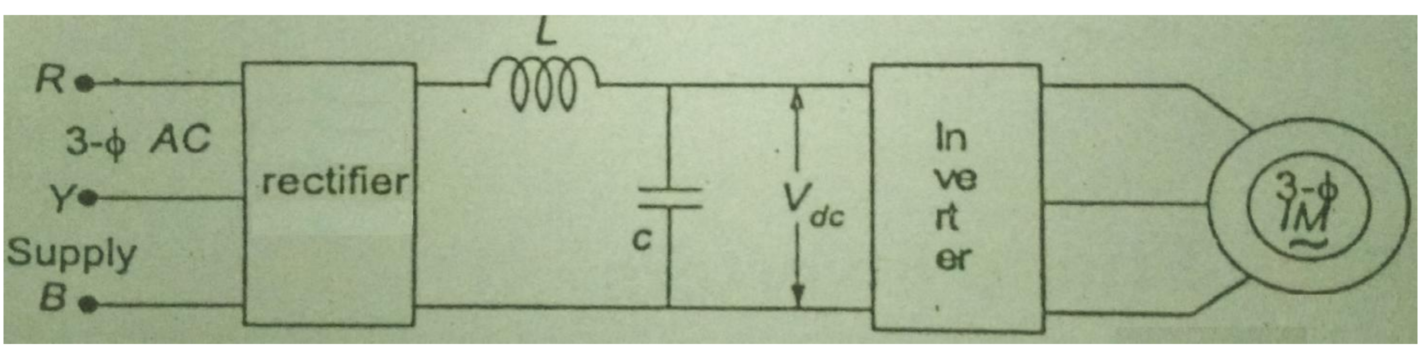
•Voltage source inverter

•Current source Inverter

-The rectifier can be controlled/uncontrolled

-Inverter can be PWM/square wave

-Here output voltage & frequency can be controlled



IV. V/F control of Induction motor

Mathematically, the relation between the speed of an induction motor and the synchronous Speed (speed of rotating flux) can be stated as:

$$Nr = (1-s)\ Ns \ \&\ Ns = 120f/p$$

Where, Nr = rotor speed
Ns = synchronous speed.
s = slip
f = supply frequency

As speed is a function of frequency and no. of poles, speed can be varied by varying these parameters.

Induction motor speed variation can be easily achieved for a short range by either stator voltage control or rotor resistance control. But at low speed it result in low efficiency. The most efficient scheme for speed control of induction motor is by varying supply frequency. This results in scheme with wide speed range but also improves the starting performance.

Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

$$Ns = 120f/p$$

In three phase induction motor emf is induced by induction similar to that of transformer which is given by

$$E \text{ or } V = 4.44\ \Phi\ K\ T\ f$$

or

$$\Phi = \frac{V}{4.44\ K\ T\ f}$$

Where, K is the winding constant, T is the number of turns per phase and f is frequency.

Or

$$\Phi \propto V/f \text{ ----- (1)}$$

or

$$V = \Phi * f$$

Voltage induced in stator is proportional to the product of supply frequency and air-gap flux. If stator drop is neglected, terminal voltage can be considered proportional to the product of frequency and flux.

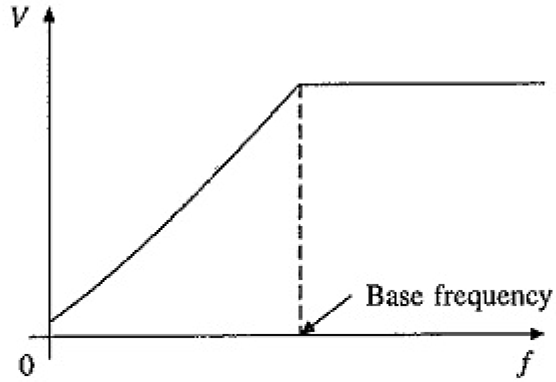
From equation (1) any reduction in the supply frequency, without a change in the terminal voltage, causes an increase in the air-gap flux. Induction motors are designed to operate at the knee point of the magnetization characteristic to make full use of the magnetic material. Therefore, the increase in flux will saturate the motor. This will increase the magnetizing current, distort the line current and voltage, increase the core loss and the stator copper loss, and produce a high-pitch acoustic noise. While an increase in flux beyond the rated value is undesirable from the consideration of saturation effects.

According to equation (1) , if we increase the frequency then the flux start to decrease. The torque developed on motor shaft is proportional to the strength of the rotating flux. Reduced flux reduces the torque capability and affects the motor ability to handle the load. So an increase/decrease in flux beyond rated value is undesirable.

Therefore, variable frequency control below rated speed is carried out by varying the terminal voltage along with frequency so as to **maintain the V/f ratio constant at rated value.**

For speed above rated speed, V/f ratio cannot be maintained constant since terminal voltage cannot be increased above rated value. So terminal voltage is kept at rated value and frequency is varied to get speed above rated speed. As frequency increases, flux decreases & hence torque produced by motor decreases.

The variation of terminal voltage with frequency in v/f control is shown in figure

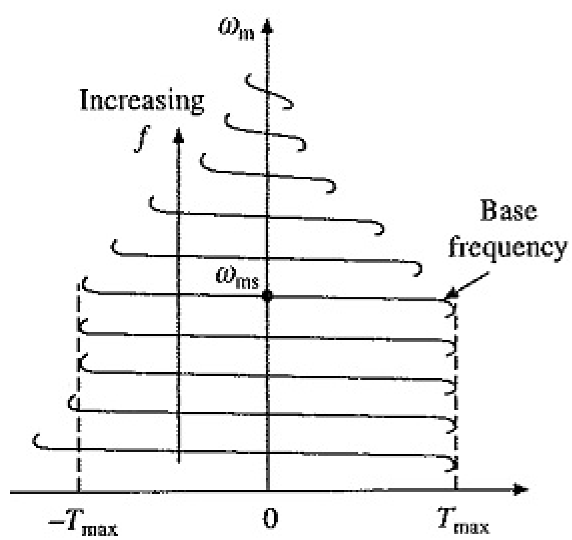


(a) V-f relation

V is kept constant above the base speed. Below the base speed (V/f) ratio is maintained constant, except at low frequencies where (V/f) ratio is increased to keep maximum torque constant.

Upto base frequency or base speed (V/f) ratio is kept constant to get maximum torque. i.e. change in frequency by a factor is done on voltage also. Above the base frequency (base speed) voltage is kept as rated voltage.

The variation of speed- torque characteristics in V/f control is shown in figure



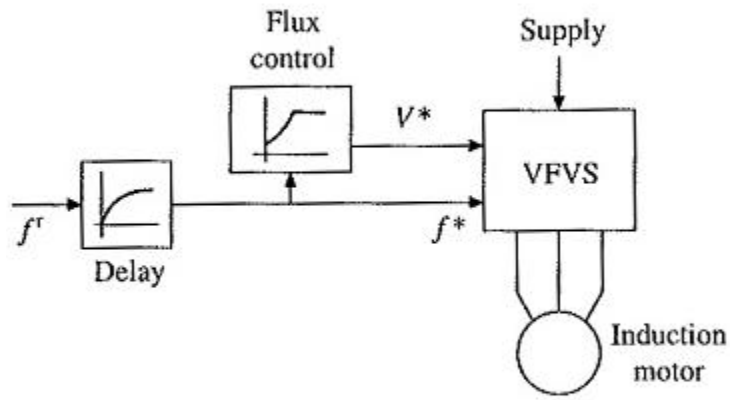
Speed-torque characteristics

The above figure shows both for motoring and braking operations. The curves suggest that speed control and braking operation are available from nearly zero speed to above synchronous speed. A given torque is obtained with a lower current when the operation at any frequency is restricted between the synchronous speed and the maximum torque point, both for motoring and braking operations.

The Variable Frequency Control of Induction Motor Drive provides good running and transient performance because of the following features:

- Speed control and braking operation are available from zero speed to above base speed.
- During transients (starting, braking and speed reversal) the operation can be carried out at the maximum torque with reduced current giving good dynamic response.
- Copper losses are low, and efficiency and power factor are high as the operation is restricted between synchronous speed and maximum torque point at all frequencies.
- Drop in speed from no load to full load is small.

The most important advantage of Variable Frequency Control of Induction Motor Drive is that it allows a variable speed drive with above-mentioned good running and transient performance to be obtained from a squirrel cage induction motor. The squirrel cage motor has a number of advantages over a dc motor. It is cheap, rugged, reliable and longer lasting. Because of the absence of commutator and brushes, it requires practically no maintenance, it can be operated in an explosive and contaminated environment, and can be designed for higher speeds, voltage and power ratings. It also has lower inertia, volume and weight. Though the cost of a squirrel cage motor is much lower compared to that of a dc motor of the same rating, the overall cost of variable frequency induction motor drives, in general are higher. But because of the advantages listed above, variable frequency induction motor drives are preferred over dc motor drives for most applications. In special applications requiring maintenance free operation, such as underground and underwater installations, and also in applications involving explosive and contaminated environments, such as in mines and chemical industry, variable frequency induction motor drives are a natural choice. They have several other applications such as traction, mill run out tables, steel mills, pumps, fans, blowers, compressors, spindle drives, conveyers, machine tools, and so on.



Variable frequency control

Block diagram of Variable Frequency Control of Induction Motor Drive scheme is shown in above.

The motor is fed from a variable frequency variable voltage source (VFVS). V* and f* are voltage and frequency commands for VFVS. Flux control block produces a voltage command V* for VFVS in order to maintain the relationship of (v/f) between V* and f*.

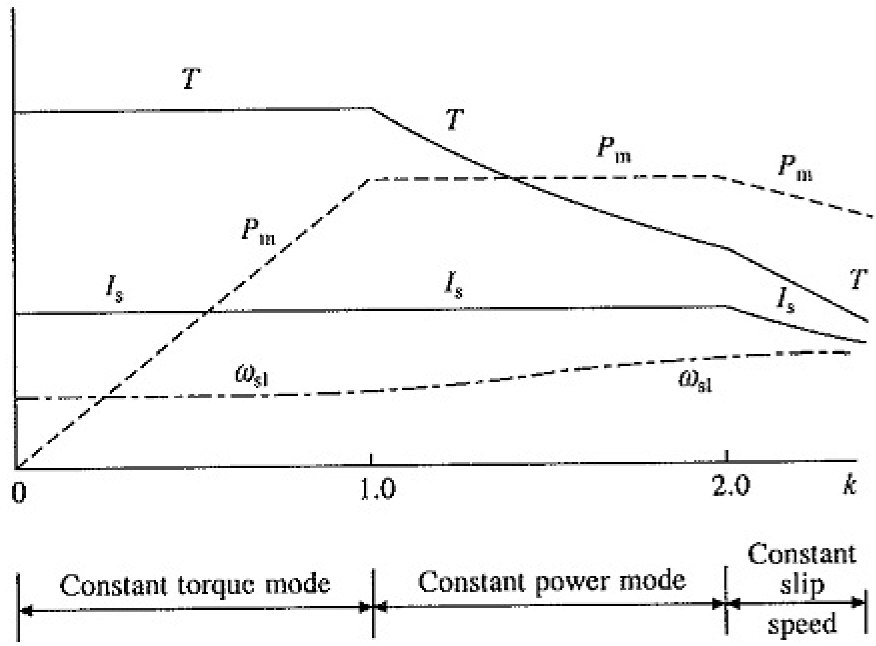
Reference frequency f* is changed to control speed. A delay circuit is introduced between f* and f^r, so that even when f^r is changed by a large amount, f* will change only slowly so that motor speed can track changes in f^r, thus restricting the motor operation for each frequency between synchronous speed and the maximum torque point. VFVS can be a voltage source inverter or a cycloconverter.

Constant torque & Constant power operation

The variation of maximum torque & power with frequency is shown in figure below

- From zero to base speed, the motor operates in constant torque mode.
- From base speed to twice the base speed, motor operates in constant power mode.

- Beyond this speed, the machine operates at a constant slip speed



Modes of operation and variations of I_s, ω_{sl}, T and P_m with per unit frequency k

Constant torque & constant power modes are present in the v/f control of induction motor below & above base speed

Constant torque mode

Induction motor operates in constant torque mode for speed control below base speed by v/f control

To get speed below base speed, supply frequency is decreased by keeping v/f ratio constant. The motor current remains constant at maximum rated value

So as voltage is varied to keep v/f ratio constant, power produced by motor varies. Since v/f ratio & hence flux is constant in machine, torque produced by machine remains constant & we get constant torque operation

Constant power mode

Induction motor operates in constant power mode for speed above base speed by v/f control

To get speed above base speed, supply frequency is increased. But stator supply voltage cannot be increased above rated voltage, so v/f ratio cannot be kept constant. The motor current remains at maximum rated value.

Since motor current & voltage are constant, power produced by motor remains constant & we get constant power operation

- When frequency increases, flux in the machine decreases & torque produced by machine also decreases as shown
- So constant power mode is also called field weakening mode of an induction motor
- For speed above twice base speed, machine operates at a constant slip speed & maximum current & power decreases
- The operation in this region is used in drives requiring wide speed range but low torque at high speeds, like in traction
- This region of operation is also called high speed series motoring region
- The variable voltage variable frequency supply for induction motor control can be obtained from an inverter or cycloconverter

V. Rotor Resistance Control of Induction Motor

Speed of an induction motor can be controlled below rated speed by rotor resistance control method

- This method is applicable only to SRIM

Torque equation of an induction motor is, $T \alpha \dfrac{sR_2E_2^2}{R_2^2 + (sX_2)^2}$

- When machine runs at near synchronous speed, slip is very low & the term $(sX_2)^2$ become very small compared to R_2

- So it can be neglected, i.e, T α (s/R_2)

- If the load torque (T) remains constant, when R_2 varies ‘s‘ also varies

- So slip & hence speed can be controlled by varying rotor resistance

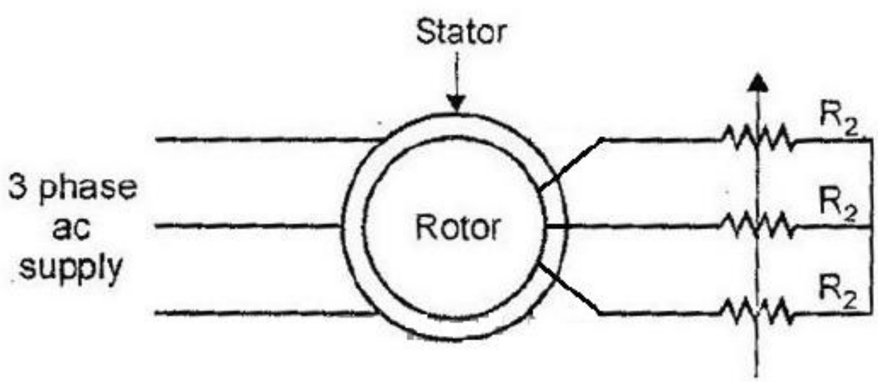
- The additional rotor resistance improves starting torque

- But it causes additional wastage of power in rotor resistance in the form of I^2R loss

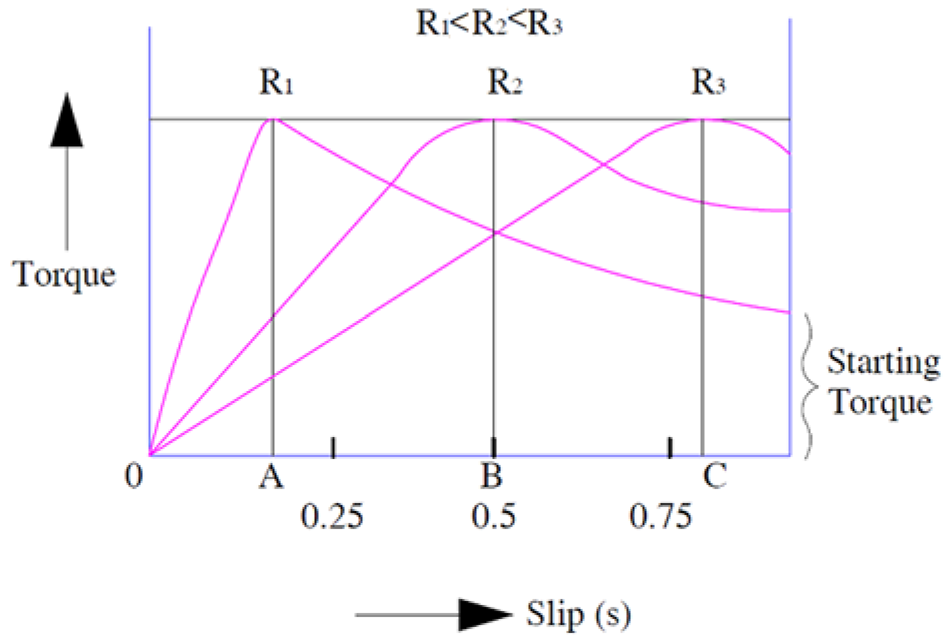
Rotor resistance control is one among the various methods for the speed control of induction motor. In this method of speed control, the rotor circuit resistance is varied by connecting a variable external resistance. This method is only applicable for slip ring or wound rotor induction motor (WRIM). As in squirrel cage induction motor (SCIM), rotor windings terminals are not available for external connection; its speed cannot be regulated by rotor resistance control. Therefore, this method is not applicable for squirrel cage induction motor.

Principle of Rotor Resistance Control (Conventional Rotor resistance control)

We know that, the torque in an induction motor is depends on the rotor circuit resistance. Also, the maximum torque is independent of rotor resistance but the slip at which this maximum torque occurs is directly proportional to the rotor circuit resistance.



Therefore if we change the rotor resistance, the maximum torque will remain constant but the slip will increase. Figure below shows the torque slip characteristics for three different rotor resistance R_1, R_2 and R_3.



In the above figure, the maximum torque is same for rotor resistance R_1, R_2 and R_3 but the slip increase from point A to B & C. This means, increasing rotor resistance results in increase in slip. Increase in slip in turn means reduction in induction motor speed. Thus we can say that by rotor resistance control, we can achieve variable speed at a constant torque. This is the reason; this method is suitable for constant torque drive.

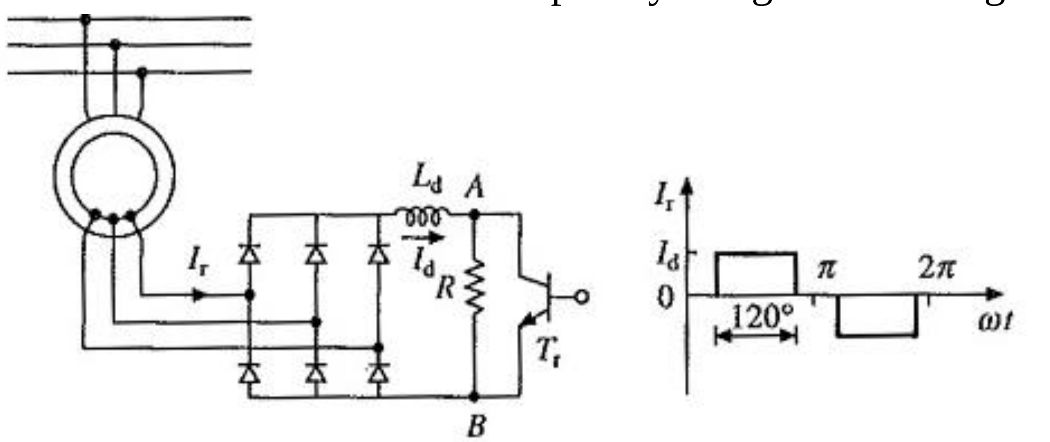
It may also be noted from the above torque slip characteristics that, starting torque increases with increase in rotor resistance. Therefore this method is advantageous where we require high starting torque.

In spite of the above two advantages of rotor resistance control, this method have some disadvantage:

- This method cannot be employed for speed control of squirrel cage induction motor. This is because of non-availability of rotor winding terminals for external resistance connection.
- This method is not very efficient. Losses in external resistance and losses in carbon brushes at high slip operation cause wastage of energy.

Static Rotor Resistance Control (Rotor chopper speed control or Chopper Resistance In The Rotor Circuit)

Rotor resistance can also be varied steplessly using circuit of Fig.



(a) Circuit diagram (b) Rotor current waveform

Rotor resistance control employing semiconductor converters

The ac output voltage of rotor is rectified by a diode bridge and fed to a parallel combination of a fixed resistance R and a semiconductor switch realized by a transistor T_r (Chopper).

Effective value of resistance across terminals A and B, R_{AB}, is varied by varying duty ratio of transistor Tr, which in turn varies rotor circuit resistance.

The resistance connected across the output terminals of a Chopper, resistance can be varied from 0 to R by varying the time ratio of the chopper. When the chopper is always OFF, the supply is always connected to the resistance R. The time ratio in this case is and the effective resistance connected is R. Similarly when the chopper is always ON, the resistance is short circuited. The time ratio in this case is unity and the effective resistance connected is 0. Hence by varying the time ratio from 0 to 1 the value of resistance can be varied from R to 0.

The slip power of the rotor is rectified by a diode rectifier and is fed to the **chopper controlled resistance**. The torque-speed curves can be drawn for different time ratios. For a time ratio of 1 we get normal characteristic of the motor. For a time ratio of 0 the characteristic corresponds to the one with complete resistance in the rotor circuit

Inductance L_d is added to reduce ripple and discontinuity in the dc link current I_d. Rotor current waveform will be as shown. in Fig. when the ripple is neglected. Thus rms rotor current will be

$$I_r = \sqrt{\frac{2}{3}}\, I_d$$

Resistance between terminals A and B will be zero when transistor is on and it will be R when it is off. Therefore, average value of resistance between the terminals is given by

$$R_{AB} = (1 - \delta)R$$

where δ is the duty ratio of the transistor. Power consumed by R_{AB} is

$$P_{AB} = I_d^2\, R_{AB} = I_d^2 R(1 - \delta)$$

Power consumed by R_{AB} per phase is

$$\text{Power consumed per phase} = \frac{P_{AB}}{3} = 0.5R(1 - \delta)\, I_r^2$$

From above equation, the rotor circuit resistance per phase is increased by $0.5R(1 - \delta)$. Thus, total rotor circuit resistance per phase will now be

$$R_{rT} = R_r + 0.5R\,(1 - \delta)$$

R_{rT} can be varied from R_r to $(R_r + 0.5R)$ as δ is changed from 1 to 0.

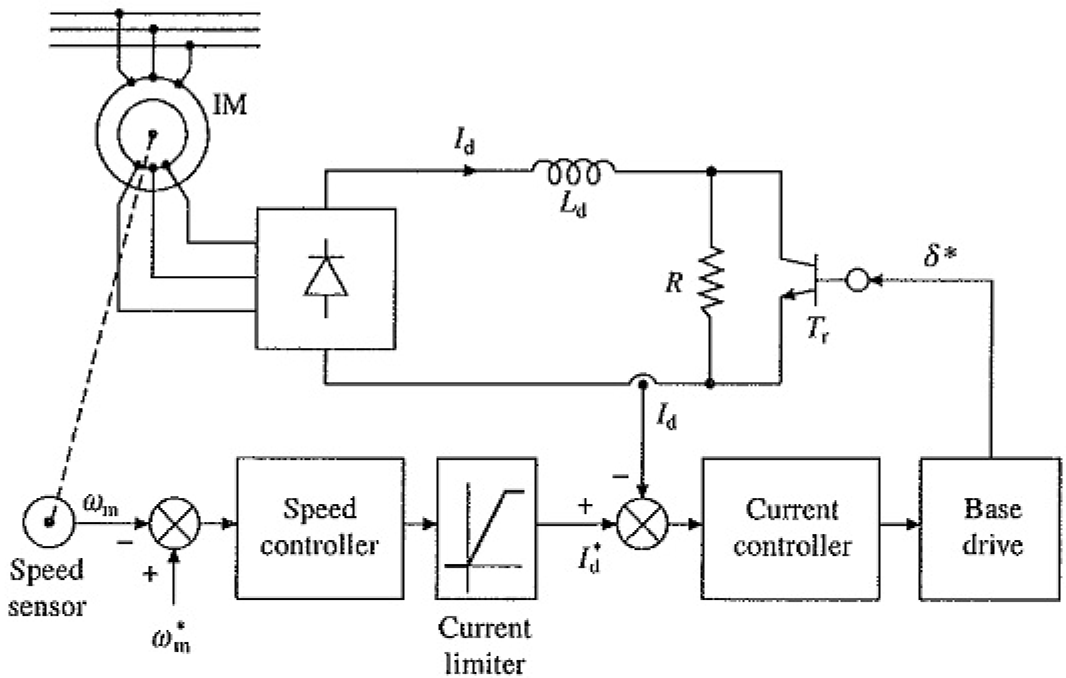
The rating of the chopper thyristor decides the maximum rotor current of the motor. The speed control range is limited by the resistance. The method is very inefficient because of losses in the resistance. It is suitable for intermittent loads such as elevators. At low speeds, in particular, the motor has very poor efficiency. Because of the increased rotor resistance, the power factor is better.

The rotor current in this case is non-sinusoidal. The harmonics of the rotor current produce torque pulsations. These have a frequency which is six times the slip frequency. The maximum torque developed is decided by the current carrying capacity.

The range of speed control can be increased if a combination of stator voltage control and rotor resistance control is employed. Instead of using a high resistance rotor, a slip ring rotor with external rotor resistance can be used when stator voltage control is used for controlling the speed

A closed-loop speed control scheme with inner current control loop is shown in Fig.

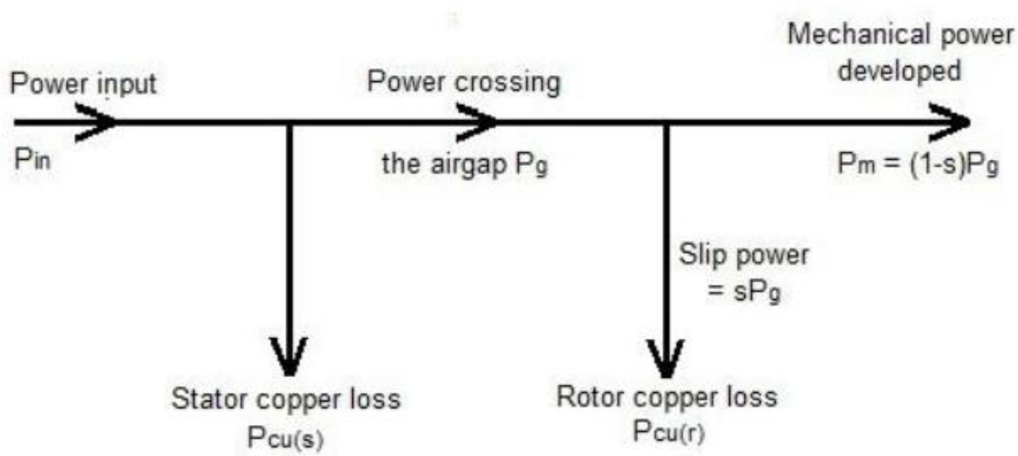
Rotor current I_r and therefore, I_d has a constant value at the maximum torque point, both during motoring and plugging. If the current limiter is made to saturate at this current, the drive will accelerate and decelerate at the maximum torque, giving very fast transient response. For plugging to occur, arrangement will have to be made for reversal of phase sequence.



Closed-loop speed control with static rotor resistance control

Compared to conventional Rotor Resistance Control of Induction Motor, static rotor resistance control has several advantages such as smooth and stepless control, fast response, less maintenance, compact size, simple closed-loop control and rotor resistance remains balanced between the three phases for all operating points.

Principle of Slip power recovery scheme



- P_{in} is the total stator input power

- Some power is wasted in stator winding as stator copper loss ($P_{cu}(s)$)

- Remaining power is crossing the air gap to reach rotor.

i.e air gap power $P_g = P_{in} - P_{cu}(s)$

- A portion of P_g is wasted in rotor resistance as rotor copper loss.

i.e given by $P_{cu}(r) = sP_g$

Remaining air gap power is converted into mechanical power,

$$P_m = (1-s)P_g$$

- The portion of air gap power which is not converted into mechanical power is called slip power

- Normally in an induction motor, slip power is wasted in rotor resistance as heat

- When rotor resistance control is used for speed control of SRIM, we are controlling the slip power to control the speed of motor

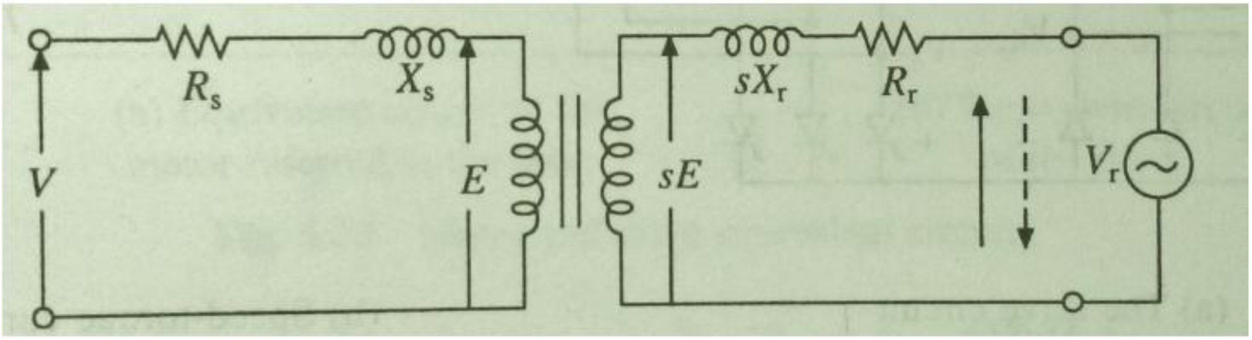
- When rotor resistance increases, speed of motor decreases

- Actually when rotor resistance increases, rotor copper loss increases. i.e, slip power increases. As a result mechanical power developed decreases because, $P_g = P_{cu}(r) + P_m$

- Instead of wasting the slip power in rotor resistance, we can recover this power & can be fed back to supply

- This method of speed control is called slip power recovery scheme

The equivalent circuit of a SRIM is shown in figure



Slip Power Recovery Scheme used in Induction Motor – Figure shows an equivalent circuit of a wound-rotor induction motor with voltage Vr injected into its rotor, assuming stator-to-rotor turns ratio unity.

When rotor copper loss is neglected- **Now we can write, $P_m = P_g – P_r$,**

where Pr is the power absorbed by the source Vr

- The magnitude & sign of P_r can be controlled by controlling the magnitude & phase of V_r.

- *When $P_r = 0$, motor runs on its natural speed torque characteristics*

- *A positive Pr will reduce Pm, and therefore, motor will run at a lower speed for the same torque*

- *When Pr is made equal to Pg, then Pm and consequently speed will be zero.*

- So variation of P_r from 0 to P_g will allow speed control from synchronous to zero speed

- Polarity of V_r for this operation is shown by continuous line

- When Pr is negative, i.e. Vr acts as a source of power, Pm will be larger than Pg and motor will run at a speed higher than synchronous speed.

- Polarity of Vr for speed control above synchronous speed is shown by a dotted line in Fig.

Here speed control below synchronous speed is obtained by controlling the slip power, the same approach used in rotor resistance speed control

- For speed above synchronous speed, additional power to be supplied to rotor

When rotor copper loss is neglected, **Pr is equal to Slip Power Recovery Scheme used in Induction Motor, sPg.** Speed control below synchronous speed is obtained by controlling the slip-power. The same approach was adopted in rotor resistance control.

However, instead of wasting power in external resistors, it is usefully employed here. **Therefore, these methods of speed control are classified as Slip Power Recovery Scheme used in Induction Motor recovery schemes.**

Two such schemes, **Static Sherbius and Static Kramer Drives**, are described here.

1. Static Kramer Drive:

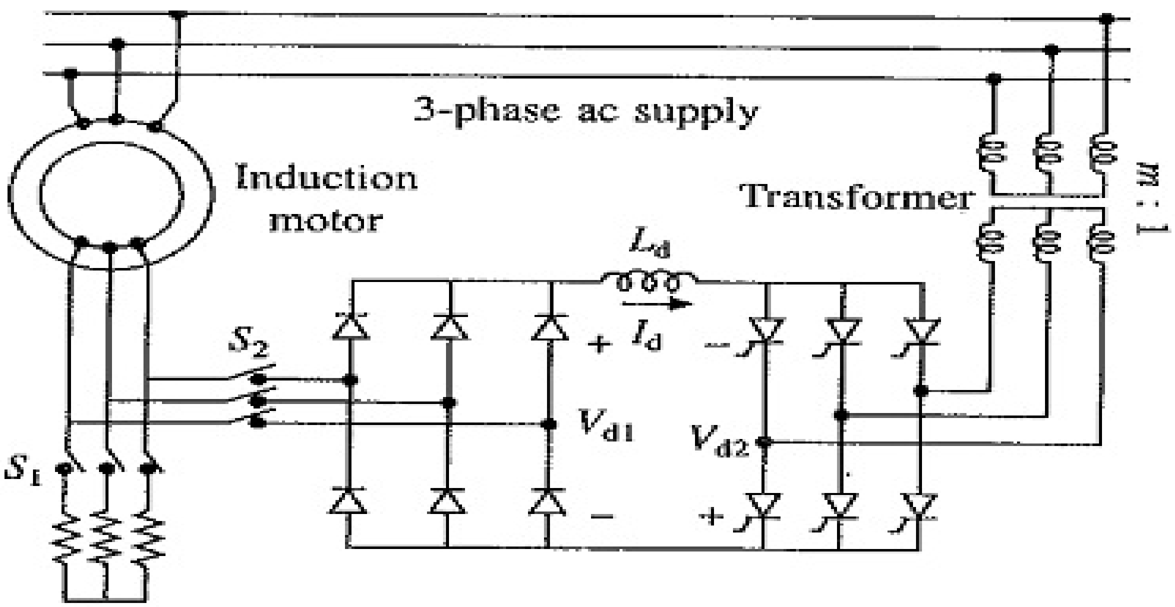
It provides the speed control of a wound rotor motor below synchronous speed.

A portion of rotor ac power is converted into dc by a diode bridge. The controlled rectifier working as an inverter converts it back to ac and feeds it back to the ac source. Power fed back (i.e. Pr) can be controlled by controlling inverter counter emf Vd_2, which in turn is controlled by controlling the inverter firing angle. The dc link inductor is provided to reduce ripple in dc link current I_d.

Since Slip Power Recovery Scheme used in Induction Motor is fed back to the source, unlike rotor resistance control where it is wasted in resistors, drive has a high efficiency. The drive has higher efficiency than stator voltage control by ac voltage controllers because of the same reasons.

Drive input power is the difference between motor input power and the power fed back. Reactive input power is the sum of motor and inverter reactive powers. Therefore, drive has a poor power factor throughout the range of its operation.

The circuit configuration is shown in figure



(a) The drive circuit

Drive is started by resistance control with S_1 closed and S_2 open. When speed reaches within control range of the drive, S_2 is closed to connect diode bridge and inverter is activated. Now S_1 is opened to remove the resistances.

- Here the slip frequency power from rotor is converted to DC voltage, which is then converted to line frequency AC and pumped back to the AC source

- Here slip power can flow only in one direction, so this drive offers speed control below synchronous speed only.

The drive input power is the difference between motor input power & power fed back.

The slip power from rotor is rectified to DC voltage by a diode bridge

- Inductor L_d smoothens ripples in rectified voltage Vd
- This DC voltage is then converted to AC voltage at line frequency by a line commutated inverter & fed back to AC supply
- In practice the rotor circuit voltage is less than stator supply voltage, so a **3 phase transformer** is often required between AC supply & the inverter
- The slip power fed back the source can be controlled by controlling the firing angle of inverter.

As the power flow is from rotor circuit to supply, Static Kramer drive offers constant-torque drive.

Rotor voltage per phase = *sE₂*,

where s –slip, E_2 – per phase rotor emf at stand still.

Neglecting the losess $sE_2 = sV$

From circuit diagram, neglecting stator and rotor drops,

Uncontrolled output voltage of diode rectifier,

$$= \frac{3*Maximum\ \ value\ \ of\ \ input\ \ line\ \ voltage}{\Pi*n}$$

$$= \frac{3*\sqrt{2}*\sqrt{3}*s*V}{\Pi*n}$$

$$V_{d1}=\frac{3\sqrt{6}\ sV}{\Pi*n}$$

For three- phase line-commutated inverter, average dc output voltage is

$$V_{d2}=\frac{3\sqrt{6}\ V}{\Pi*m} cos \propto$$

where α is the inverter firing angle and, n and m are, respectively, the stator to rotor turns ratio of motor and source side to converter side turns ratio of the transformer. Neglecting drop across inductor

$$V_{d1} + V_{d2} = 0$$

$$\frac{3\sqrt{6}\ sV}{\Pi*n} + \frac{3\sqrt{6}\ V}{\Pi*m} cos \propto = 0$$

$$=> s = \frac{-n}{m} \cos \propto = -a \cos \propto$$

where a = n/m.

Maximum value of α is restricted to 165° for safe commutation of inverter thyristors.

Slip can be controlled from **0 to 0.966a when α is changed from 90 to 165°.** By appropriate choice of a, required speed range can be obtained.

Transformer is used to match the voltages V_{d1} and V_{d2}. At the lowest speed required from the drive, V_{d1} will have the maximum value V_{d1m} given by

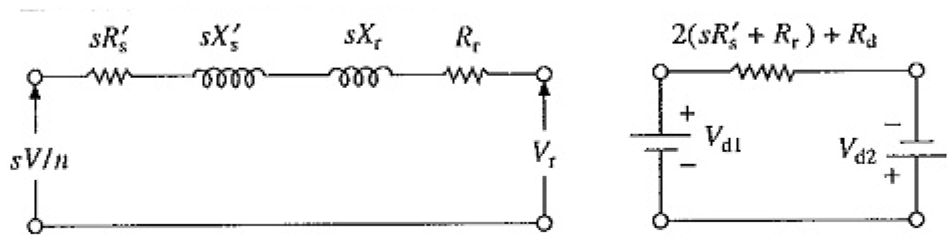
$$V_{d1m} = Vs_{max}/n$$

where s_{max}, is the value of slip at the lowest speed. If α is restricted to 165°, m is chosen such that the inverter voltage has a value V_{d1m} when α is 165° i.e.

$$\frac{V}{m} \cos 165° + \frac{Vs_{max}}{n}$$

$$m = -\frac{n \cos 165°}{s_{max}} = -0.966 \frac{n}{s_{max}}$$

Such a choice of m ensures inverter operation at the highest firing angle at the lowest motor speed, giving highest power factor and lowest reactive power at the lowest speed. This improves the drive power factor and reduces reactive power at all speeds in the speed range of the drive.



(a) Equivalent circuit of the motor referred to the rotor

(b) Equivalent circuit of the drive

Motor and drive equivalent circuits

Figure shows equivalent circuit of motor referred to the rotor, neglecting magnetizing branch.

When referred to dc link, resistance (sR′s + Rr) will be 2(sR′s + Rr). This gives approximate dc equivalent circuit of the drive where V_{d1} and V_{d2} dc voltages. R_d is the resistance of dc link inductor. Equivalent circuit ignores the commutation overlap in the diode bridge.

Now

$$I_d = \frac{V_{d1} + V_{d2}}{2(sR_s' + R_r) + R_d} = \frac{\frac{3}{\pi}\sqrt{6}\,V\left(\frac{s}{n} + \frac{\cos\alpha}{m}\right)}{2(sR_s' + R_r) + R_d}$$

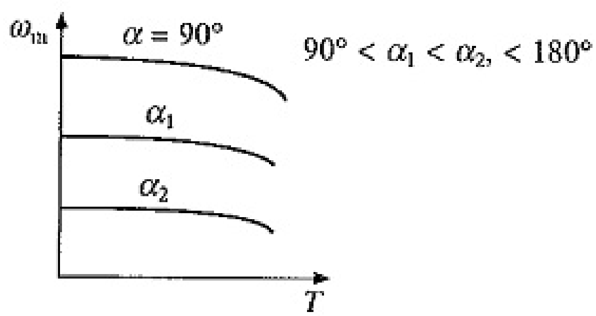
If rotor copper loss is neglected

$$sP_g = |V_{d2}|\,I_d$$

$$p_g = \frac{|V_{d2}|\,I_d}{s}$$

$$T = \frac{P_g}{\omega_{ms}} = \frac{|V_{d2}|\,I_d}{s\omega_{ms}}$$

The nature of speed torque curves is shown in Fig.

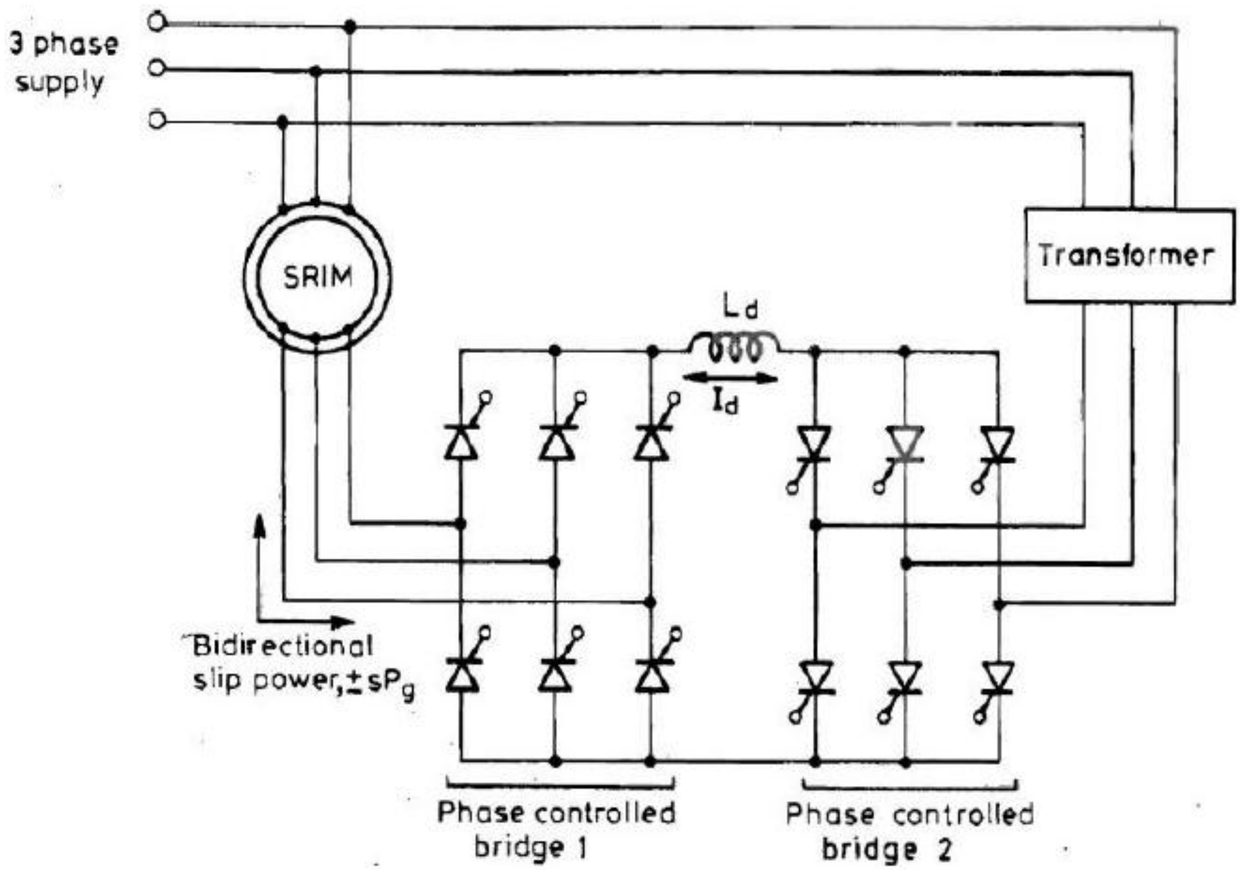


Speed-torque curves

The drive has applications in fan and pump drives which require speed control in a narrow range only. This drive is widely used in medium and high power (up to around 10 MW) fan and pump drives, because of high efficiency and low cost.

2. Static Scherbius Drive

In static Kramer Drive, speed of SRIM can be varied only below synchronous speed**.** For speed control of SRIM above & below synchronous speed, static Scherbius Drive is used The drive is shown in figure.

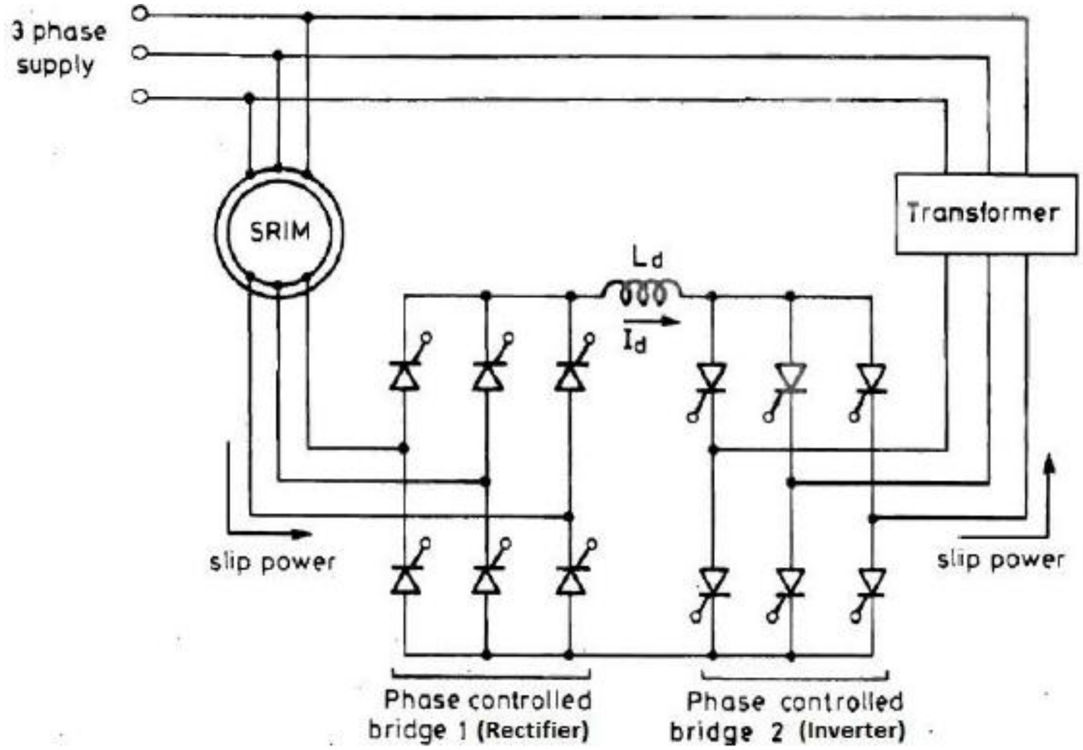


It consist of two fully controlled bridge circuits - Bridge 1 & Bridge 2

- Both bridges can work as rectifier & as inverter depending on the firing angle.

By using this drive, speed control above & below synchronous speed is possible, so it got two modes of operation

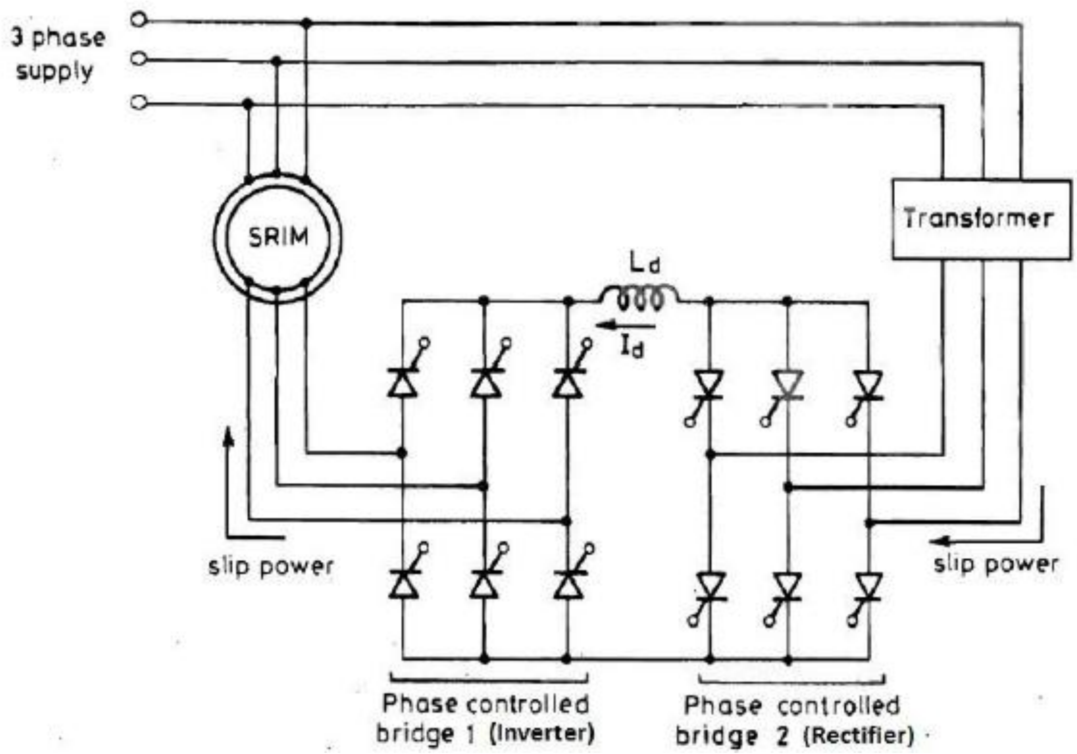
Mode 1 – Sub synchronous speed operation



- In this mode of operation, slip power is removed from the rotor circuit & is pumped back into the AC supply.
- Now, Bridge 1 works as rectifier (firing angle less than 90) & Bridge 2 works as inverter (firing angle greater than 90).
- The slip power flows from rotor circuit to bridge 1, DC link, bridge 2, transformer and returned to supply.

Mode 2 – Super synchronous speed operation

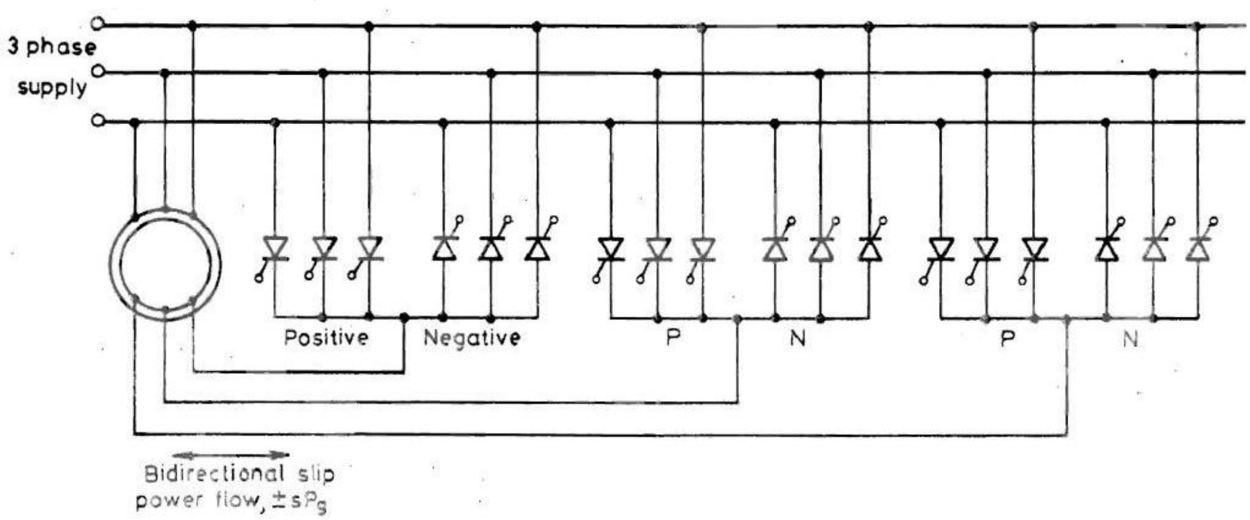
- For super synchronous speed control, additional power is fed into the rotor circuit at slip frequency
- For super synchronous speed control, bridge 1 works as an inverter (firing angle greater than 90) & bridge 2 works as a rectifier (firing angle less than 90)
- The power flow is now from supply to transformer, bridge 2, bridge 1 & to rotor circuit



- This drive is expensive than static Kramer drive, because it requires 2 controlled bridges & its control circuitry
- Here when motor speed reaches near synchronous speed, magnitude of rotor induced voltage is not sufficient to provide line commutation of thyristors. So we provide forced commutation.

Cycloconverter Scherbius drive

- Here the bridge converter system is replaced by a 3 phase controlled line commutated cycloconverter. The slip power flow in both direction



Module V

VSI & CSI fed Induction motor Drives

Variable frequency Induction motor drives

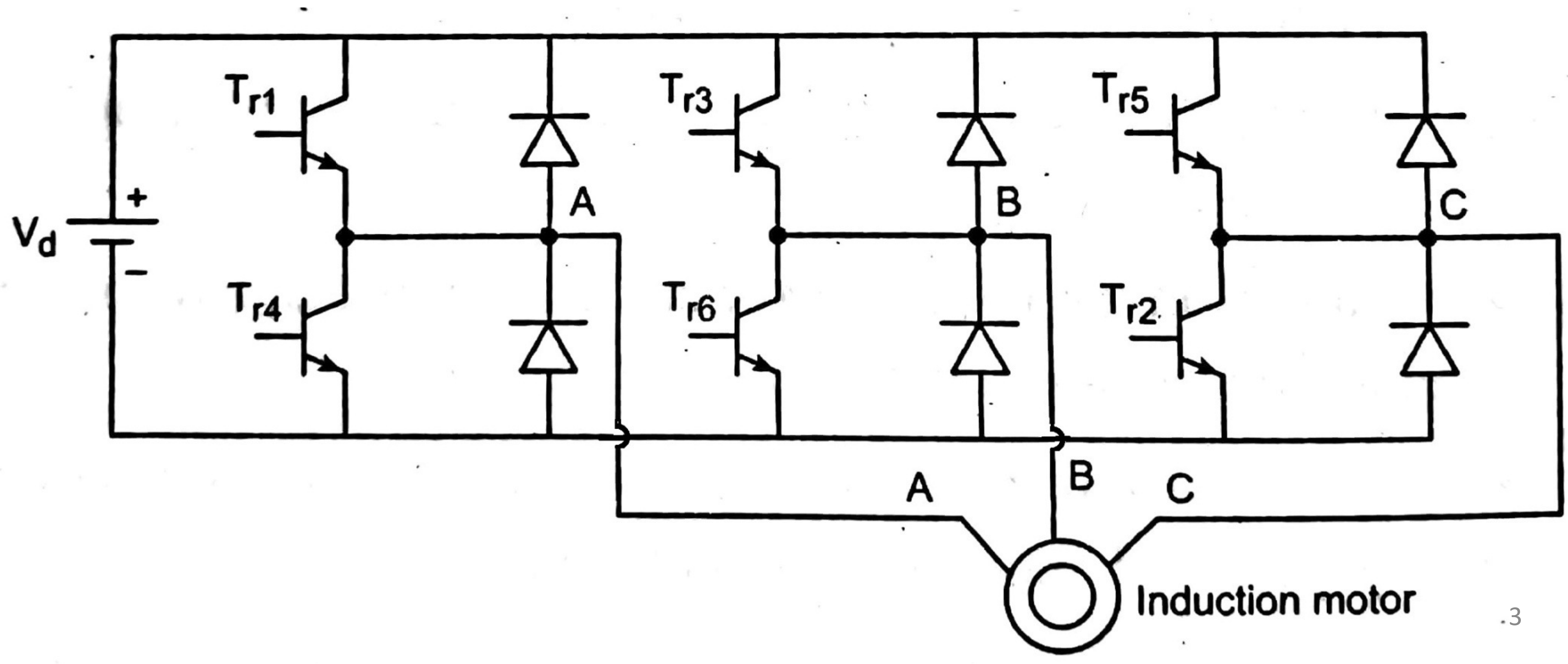
- The speed of an Induction motor can be controlled by varying the supply frequency
- Variable frequency control allows good running & transient performance
- Variable frequency Induction motor drives are utilized in fan, pump, blower, conveyor and machine tools applications
- Variable frequency AC supply can be obtained by using

1. Voltage source inverter
2. Current source inverter
3. Cycloconverter

Voltage source inverter (VSI) fed induction motor drives

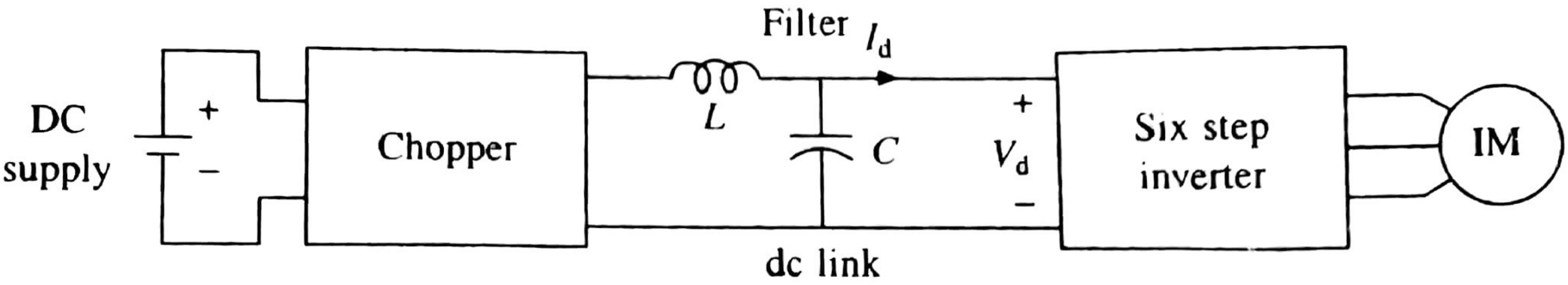
- VSI allows a variable voltage variable frequency AC supply obtained from a DC supply
- Normally self commutating devices like MOSFET, IGBT, power transistors are used in VSI

- VSI can operate as a stepped wave inverter or a PWM inverter
- In a stepped wave inverter, output frequency can be controlled by controlling the turn ON time of switches and output voltage can be controlled by controlling the input DC voltage
- In a PWM inverter, the output voltage & frequency can be controlled within the inverter by PWM technique
- Figure below shows the configuration of a VSI fed Induction motor

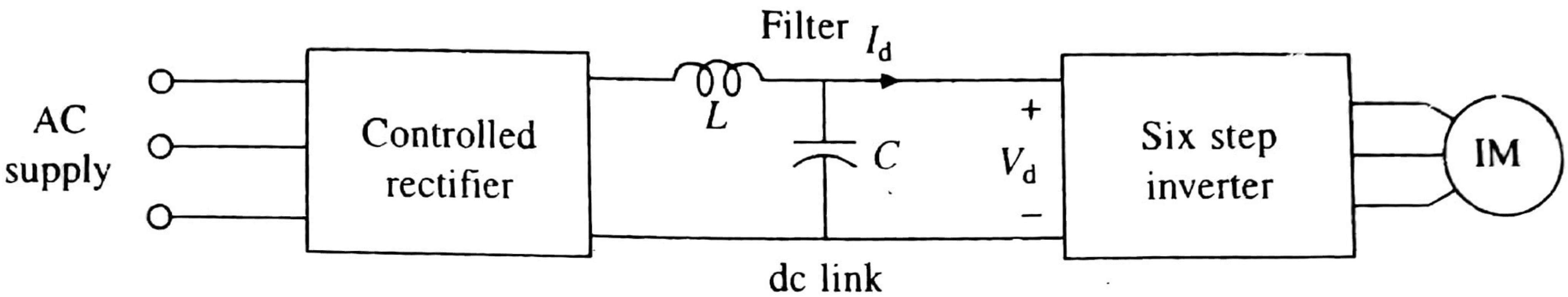


Stepped wave inverter

- When supply is DC, variable DC input is obtained by connecting a chopper between DC supply & inverter



- When supply is AC, variable DC input is obtained by connecting a controlled rectifier between AC supply & inverter



**** Stepped wave VSI fed induction motor drive has following drawbacks***

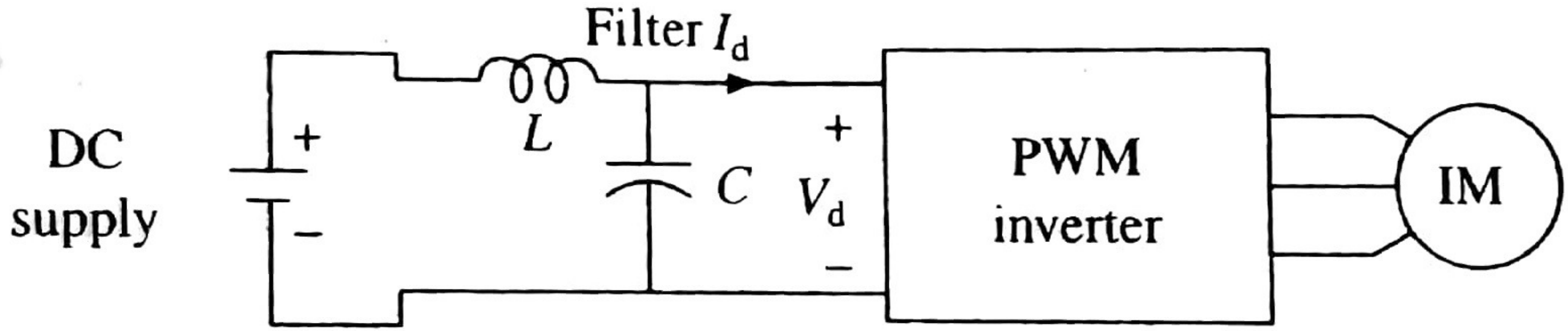
- The output voltage of inverter has large low frequency harmonic content
- Low frequency harmonics increases motor losses & causes de-rating of motor
- Motor develops pulsating torque due to harmonics (5,7,11,13)
- Harmonic content in current increases at low speeds. Machine saturates at low speeds due to high V/f ratio. These two effects overheats the machine at low speeds

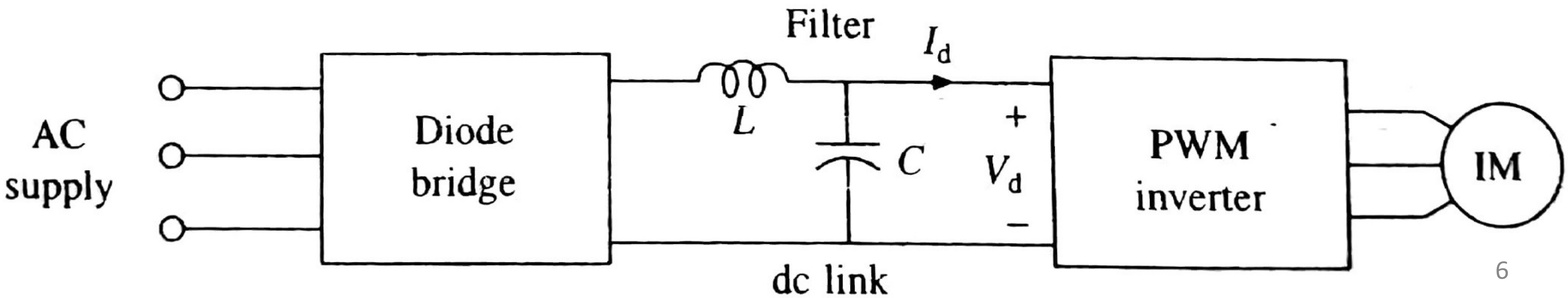
Features

- This is advantageous for multi motor drive
- Dynamic behavior is fairly good at high speeds
- Dynamic braking is possible
- Regeneration requires an additional converter connected antiparallel to line side one
- Speed reversal is achieved by changing the phase sequence

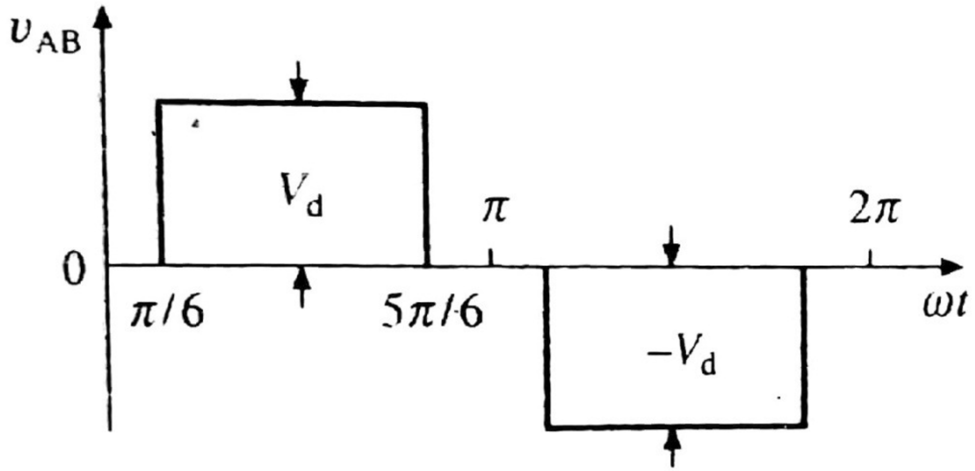
PWM inverter

- The drawbacks of stepped wave inverter can overcome by using a PWM inverter
- Here output voltage can be controlled by PWM, no arrangement is required for varying DC input voltage
- So inverter can be directly connected when supply is DC and through a diode rectifier when supply is AC

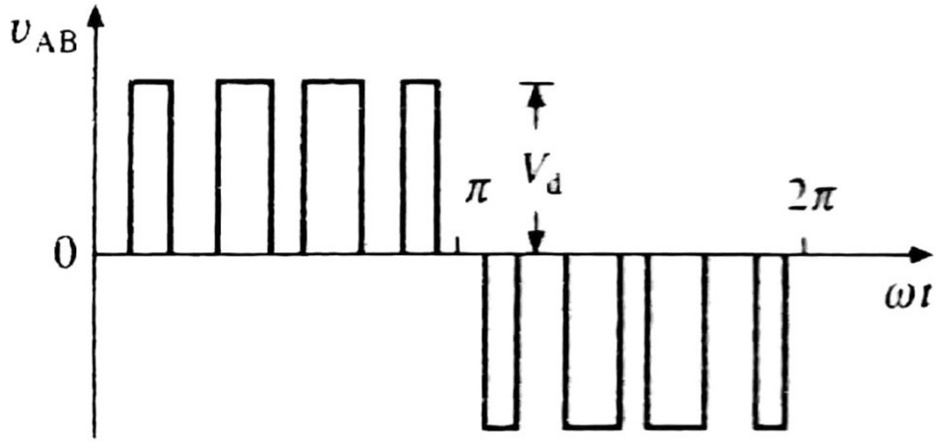




- PWM inverter has constant DC link voltage & uses PWM technique for both voltage control & harmonic elimination
- Output voltage waveform is improved (more sinusoidal), with low harmonic content
- The amplitude of torque pulsation is minimal even at low speeds
- Power factor of the system is good as a diode rectifier is used on line side
- Four quadrant operation is possible
- Dynamic braking can be employed
- Single & multi motor drive is possible
- VSI fed induction motor drive are normally powered from AC supply & regeneration is possible if the rectifier used is a full converter or dual converter
- Output voltage wave form of a stepped wave & PWM inverter are shown in next slide



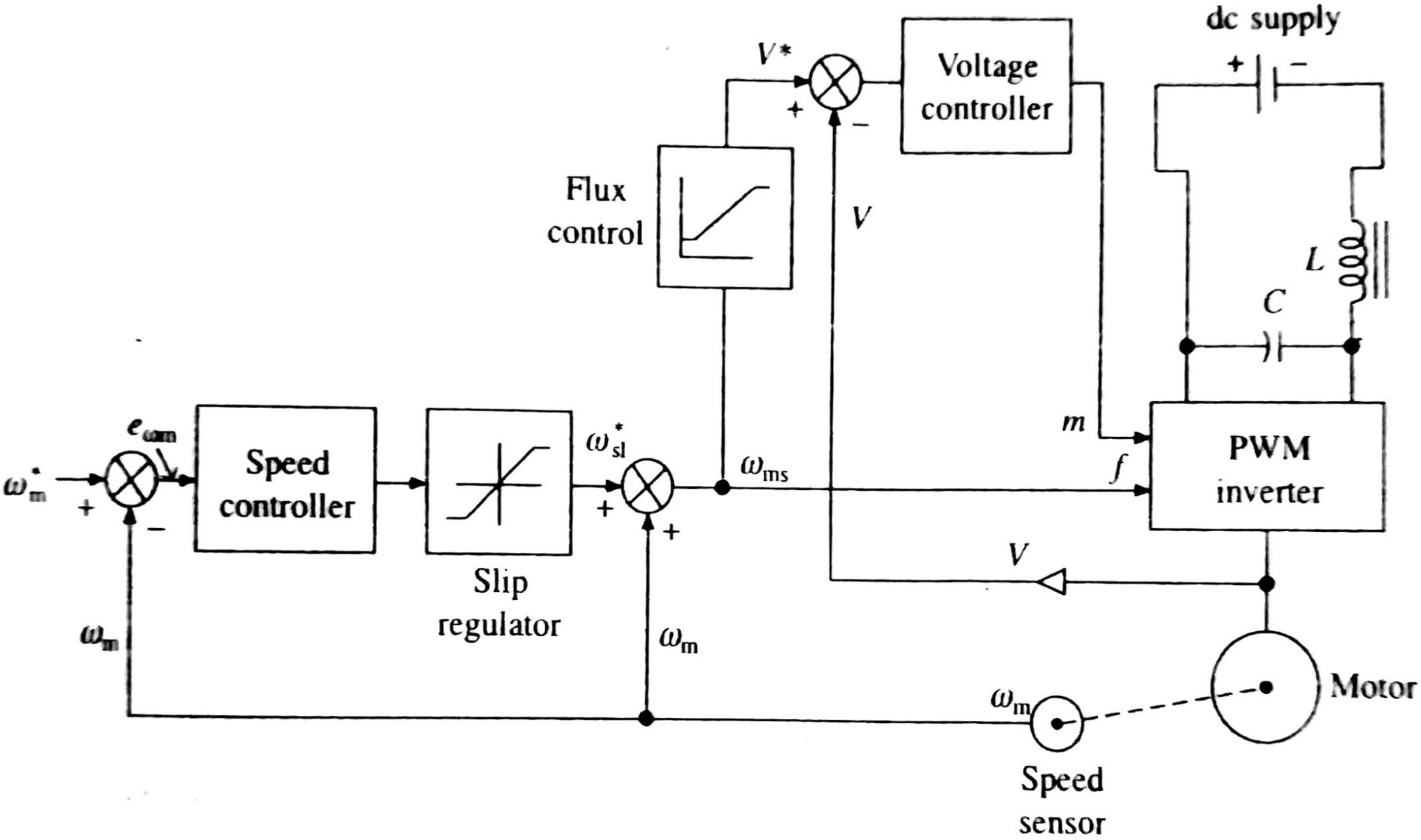
Stepped wave inverter line voltage waveform



PWM inverter line voltage waveform

Closed loop speed control of VSI induction motor drives

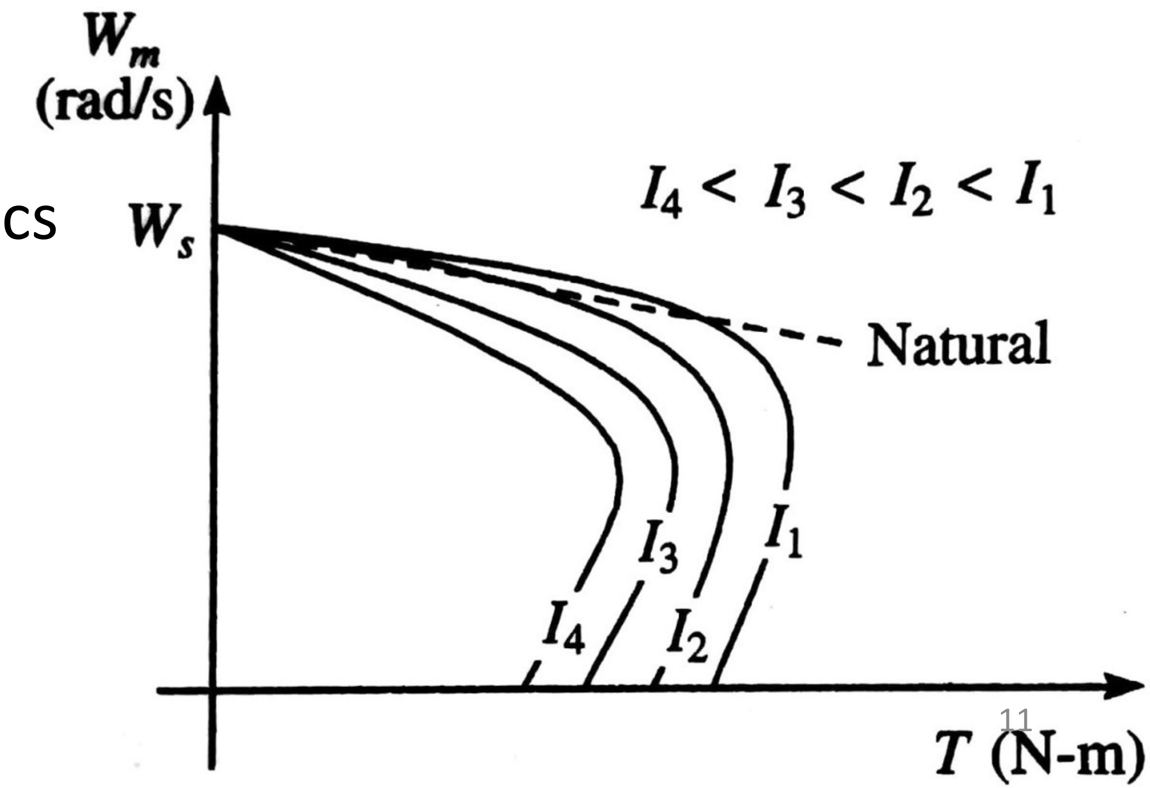
- A closed loop speed control of VSI fed IM drive is shown in figure
- It employs an inner slip speed loop & outer speed loop
- For a given current, slip speed has a fixed value. So slip speed loop also functions as an inner current loop
- Drive uses a PWM inverter fed from a DC source which has the capability for regenerative braking & 4 quadrant operation


dc supply
+
−
Voltage
controller
V^*
+
−
V
Flux
control
L
C
m
f
PWM
inverter
$e_{\omega m}$
ω_m^*
+
−
Speed
controller
Slip
regulator
ω_{sl}^*
+
+
ω_{ms}
V
ω_m
ω_m
ω_m
Motor
Speed
sensor

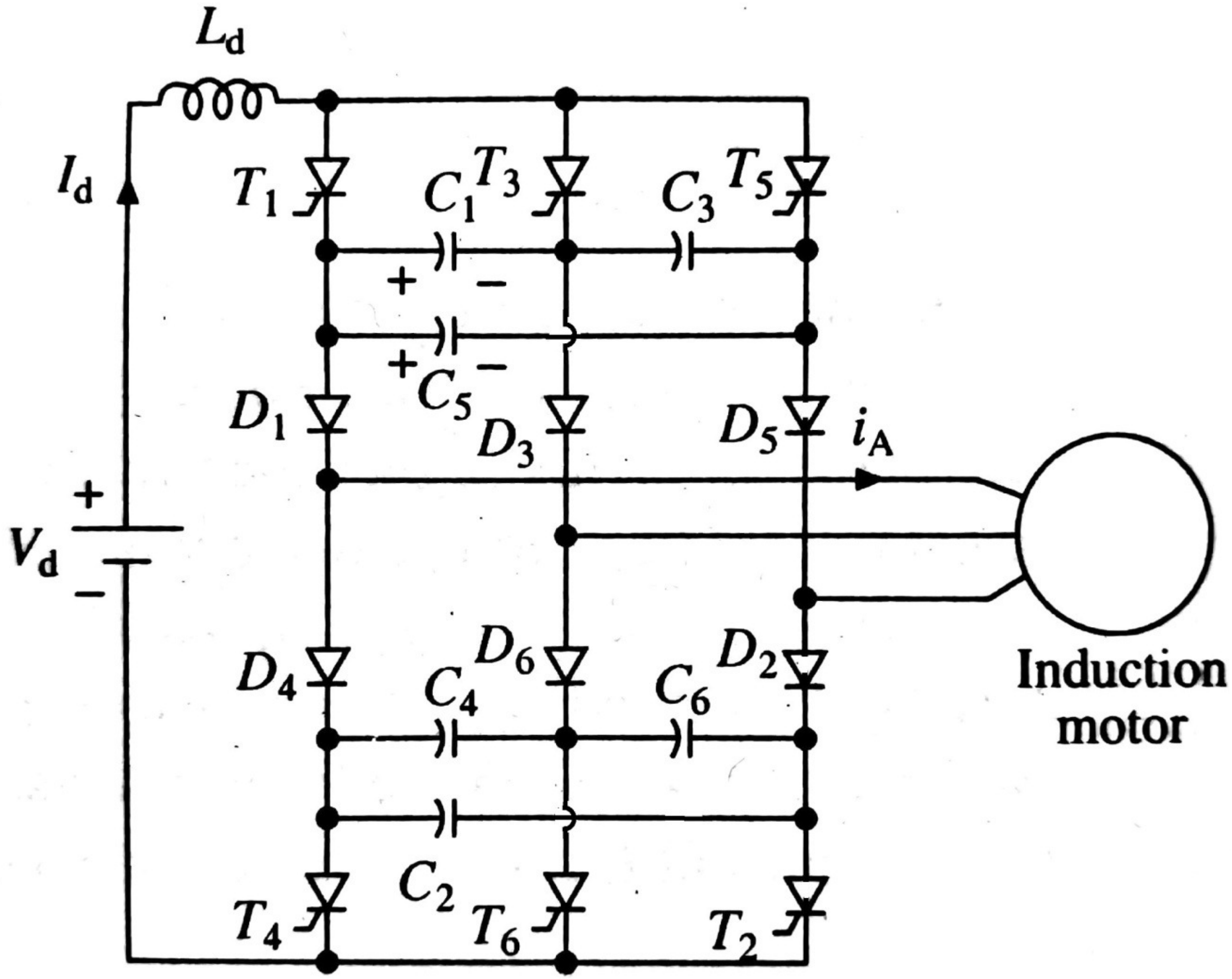
- The actual speed(ω_m) is compared with reference speed(ω_m*) to get speed error
- The reference signal (V*) for voltage control is generated from frequency(f) using a function generator
- The speed error is processed through a speed controller (PI) & a slip regulator to produce a slip speed command (ω_{sl}*)
- The synchronous speed obtained by adding actual speed & slip speed determines inverter frequency
- V* is compared with actual stator voltage to get voltage error
- The voltage error is processed by a voltage controller to produce the necessary modulation index variation

Current Source Inverter (CSI) fed Induction motor drive (stator current control)

- Here the developed torque & hence the speed of motor is controlled by stator current control
- The behavior of motor with stator current control is different from that obtained with stator voltage control
- When an induction motor is fed from a current source, the analysis shows that the maximum torque produced by motor α (stator current)^2 & is independent of frequency & rotor resistance
- The speed- torque characteristics for different stator currents are shown in figure



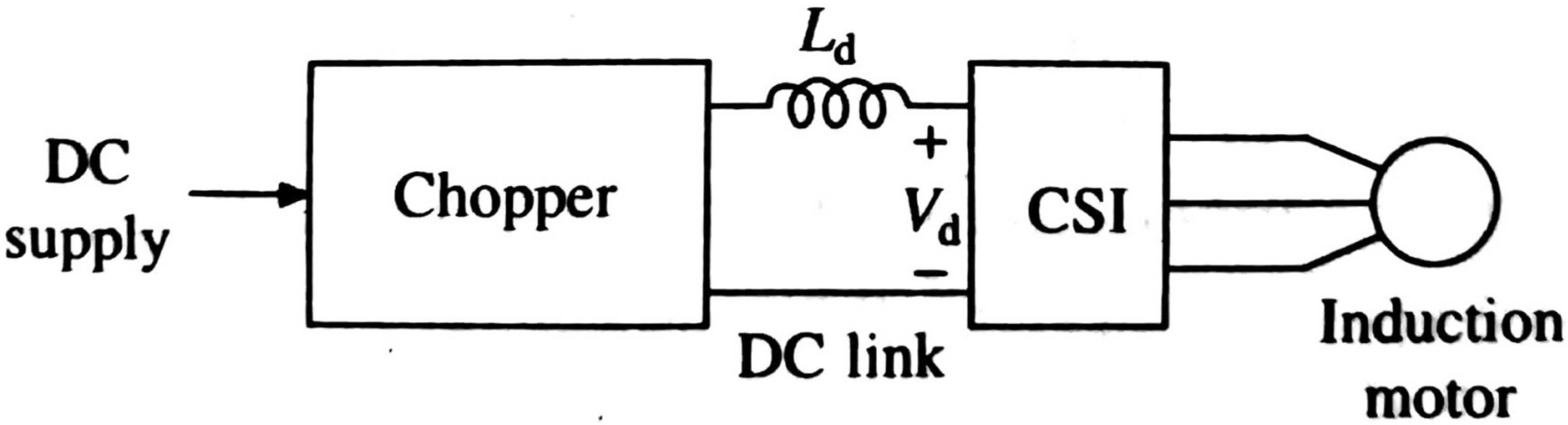
- When operating at constant flux, the operating points are located mostly on unstable region of torque – speed characteristics
- Hence closed loop control is mandatory for stable operation
- A constant current for 3 phase induction motor can be obtained from a 3 phase current source inverter (CSI)
- Figure below shows the configuration of a CSI fed Induction motor



- The two commonly used configurations for CSI fed induction motor drives based on the source available are shown below

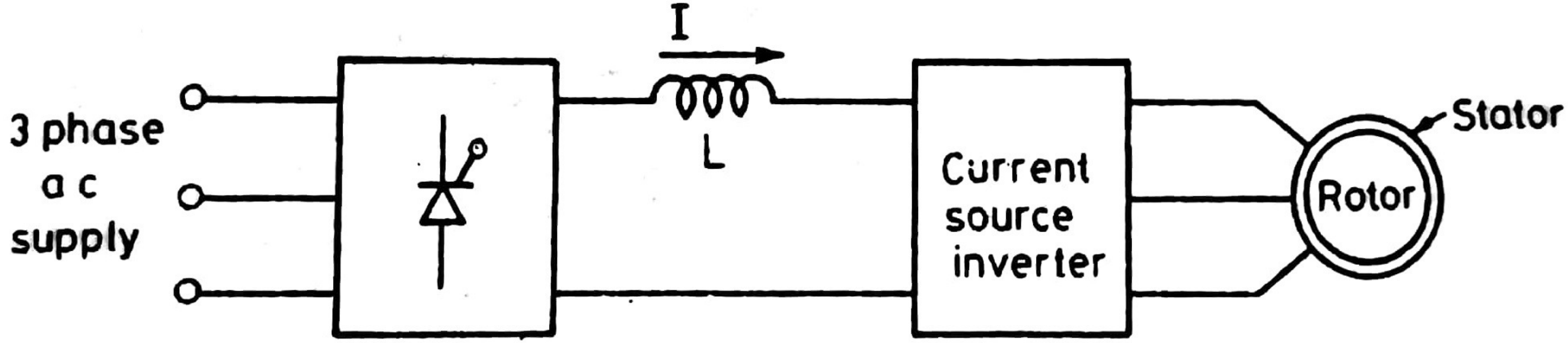
1. When source available is DC source

- Here a chopper is used in between DC source & Inverter to vary the DC link voltage

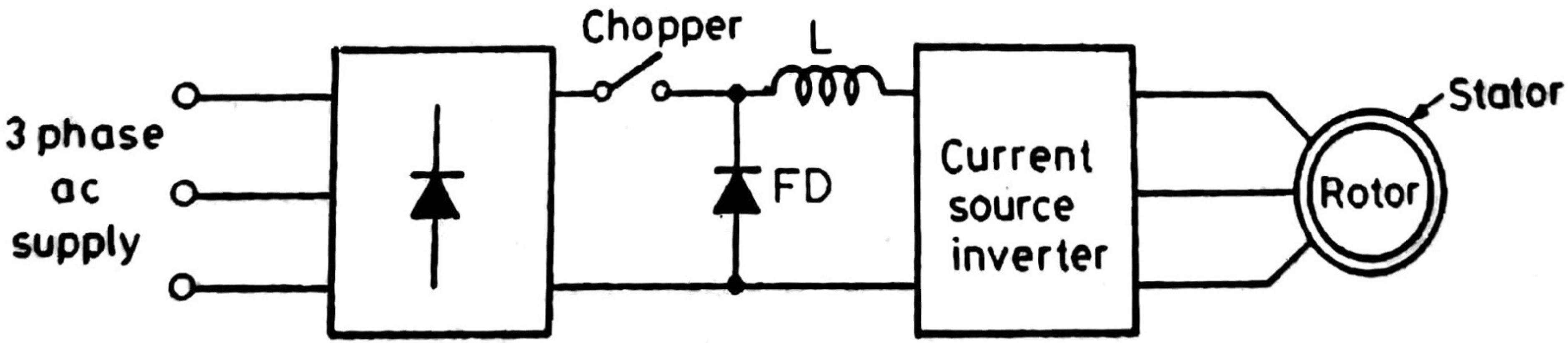


2. When source available is AC source

- Here, 3 phase controlled rectifier produces a controlled DC voltage
- Inductor converts this voltage to a constant current
- CSI regulates output frequency & therefore the torque & speed of motor



- Here one more configuration is possible, i.e if we are using a diode rectifier, the circuit configuration become as shown below



- 3 phase diode rectifier produces an uncontrolled DC voltage.
- It is regulated by using a chopper, which is then converted to current source by inductor
- CSI regulates output frequency & therefore the torque & speed of motor

Advantages & disadvantages of CSI fed IM drive

- More reliable than VSI. In VSI, commutation failure will cause short circuit across source & current rises to dangerous values. So expensive semiconductor fuses are required for safety. In CSI due to the presence of large inductance, current will not increase to dangerous values & less expensive HRC fuses are sufficient.
- Current input is unaffected by motor parameter variations
- It produce harmonics in the system
- Open loop operation is not possible
- Only single motor operation is possible
- Converter grade thyristors are sufficient
- There is stability problem at light load. A minimum current should be there for commutation
- So it finds application in medium & high power drives

Comparison of VSI & CSI fed drives

- CSI is more reliable than VSI
- Because of large inductance in DC link & large inverter capacitors (for commutation) CSI drive has higher cost, weight & volume, lower speed range, slower dynamic response
- The CSI drive is not suitable for multi motor drives. But a single VSI drive can feed a number of motors

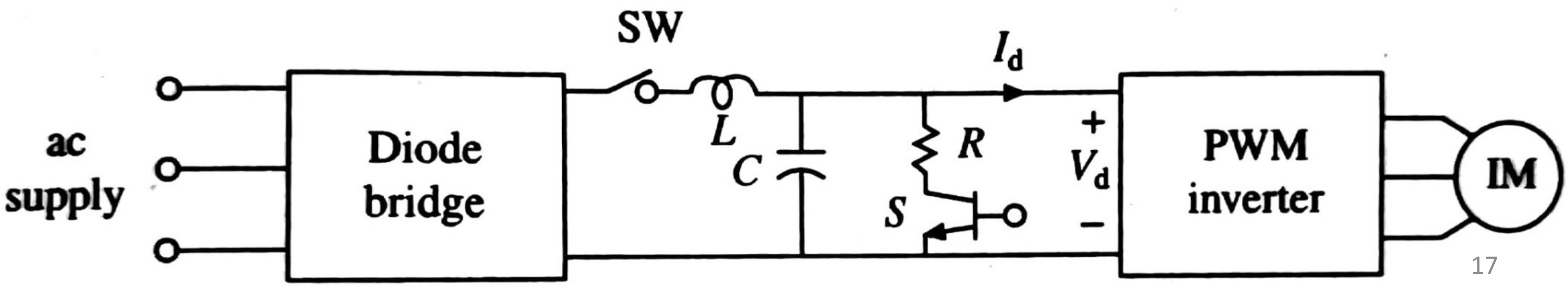
Braking of VSI fed Induction motor drives

- During motoring operation, power flows from inverter to motor
- The motor will run at a speed which is less than synchronous speed
- During braking operation, the motor works as a generator & produces electrical energy
- The induction motor will work as generator, when the actual speed of motor become greater than synchronous speed
- For braking operation, ***the inverter output frequency is reduced, so that synchronous speed become less than actual speed***

- Now motor will work as generator, produces electrical energy
- This energy is converted to DC by the inverter, which will work as a controlled rectifier during braking operation
- As a result, the direction of DC link current reverses
- The Electrical power reaching the DC link can be utilized effectively by Regenerative braking or it can be wasted in a resistor by Dynamic braking

Dynamic Braking

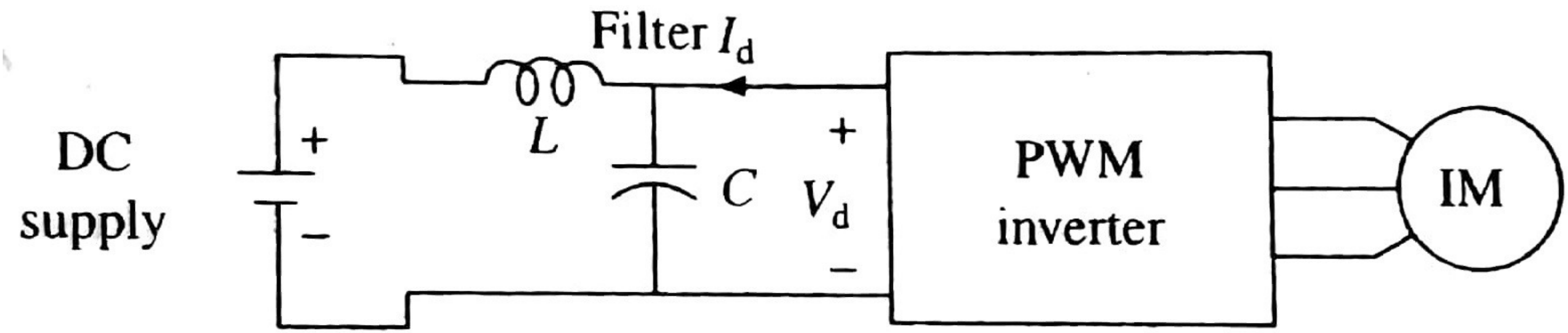
- In dynamic braking, the electrical power generated during braking operation is wasted in a resistor to get the desired braking effect
- The circuit configuration for dynamic braking of PWM inverter fed induction motor drive is shown below



- For dynamic braking, the switch SW & a self commutated switch S in series with braking resistance R connected across the DC link
- When operation of motor shifts from motoring to braking, switch SW is opened
- Generated power flowing into DC link charge the capacitor & its voltage increases
- When voltage crosses a set value, switch S is closed, connecting the resistance across the DC link
- The generated power & a part of power stored in capacitor flow into the resistance & DC link voltage reduces
- When it falls below nominal value, switch S is opened
- Thus the generated power is dissipated in the resistance giving dynamic braking
- Dynamic braking is applicable to all Induction motor drives fed from an inverter

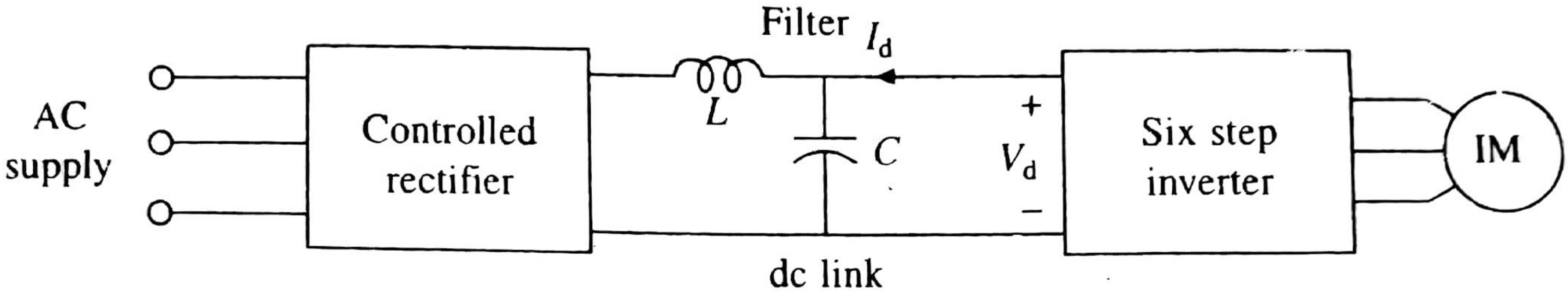
Regenerative Braking

- In regenerative braking, the electrical power generated during braking operation is effectively fed back to the supply
- Regenerative braking is not possible in all VSI fed induction motor drives
- When supplied from a DC source, regeneration is easy



- Here, during braking motor works as generator producing electrical power.
- This power reaches the DC link through PWM inverter & direction of DC link current reverses
- Now, power flow from DC link to source

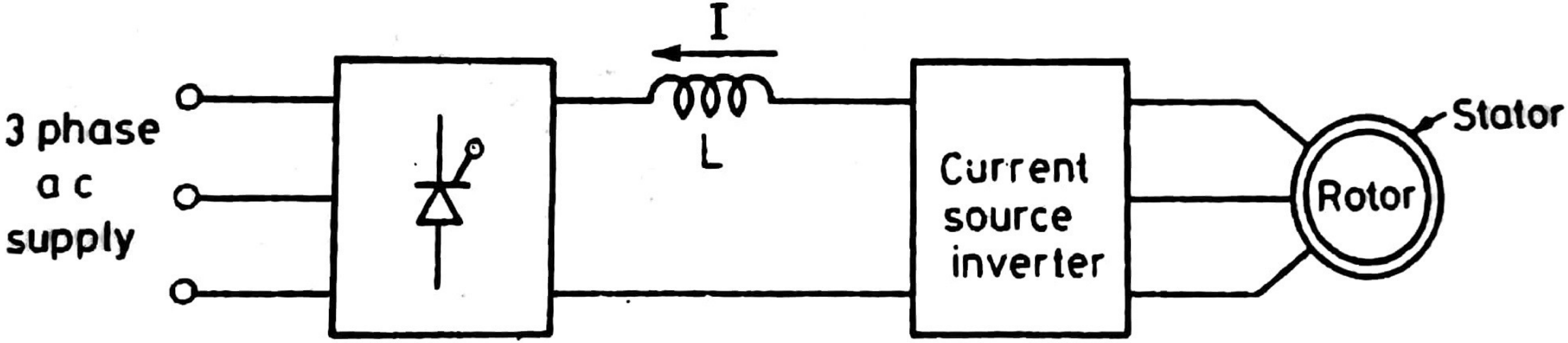
- When supplied from an AC source, for regeneration the source side converter (rectifier) should be a full converter or dual converter



- During regeneration, electrical power generated reaches DC link
- The direction of DC link current reverses
- Now the controlled rectifier/dual converter will fed back this DC link power to AC source to get regenerative braking

<u>Regenerative Braking of CSI fed Induction motor drives</u>

- When inverter frequency is reduced to make synchronous speed less than motor speed, machine works as a generator
- Power flows from machine to DC link & DC link current flow reverses

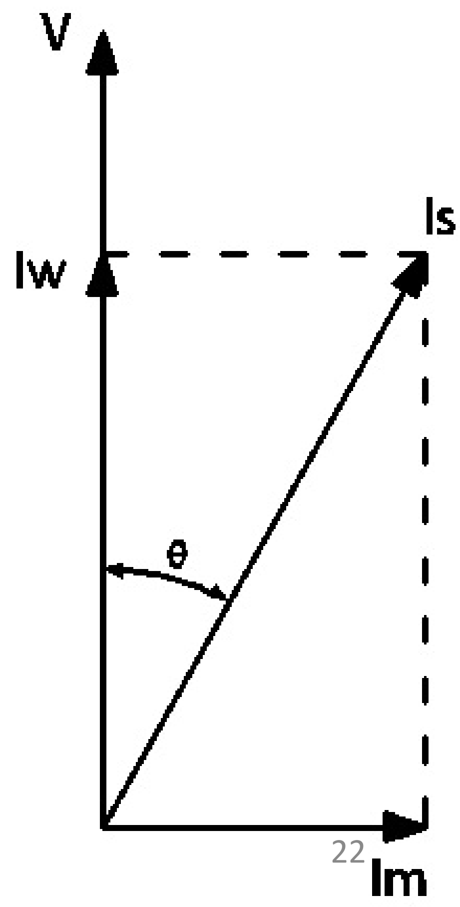


- If a fully controlled converter is made to work as an inverter, the power supplied to DC link will be transferred to AC supply & regenerative braking will take place
- Thus no additional equipment is required for regenerative braking

Basic principle of Vector Control (Field oriented control)

- In a separately excited DC motor, both field flux & electromagnetic torque can be controlled independently by varying field current & armature current respectively in the machine
- In an AC motor (eg. Induction motor) there is only one current, ie the stator current which produce both flux & torque in the machine
- So in an AC motor, by using normal control techniques, independent control of torque & flux is not possible

- Independent control of torque and flux possible in AC motor drives by using *Vector Control or Field Oriented Control (FOC)*
- In vector control, an induction motor is controlled under all operating conditions to get performance similar to a separately excited DC motor
- The stator current (I_s) of an induction motor can be resolved into 2 components - Flux producing component I_m & torque producing component I_w
- If we are able to control I_m & I_w independently, then flux & torque can be controlled independently
- In vector control we are controlling I_m & I_w independently
- There are 3 stator currents in a 3 phase induction motor & they together produce the required flux & torque inside the machine



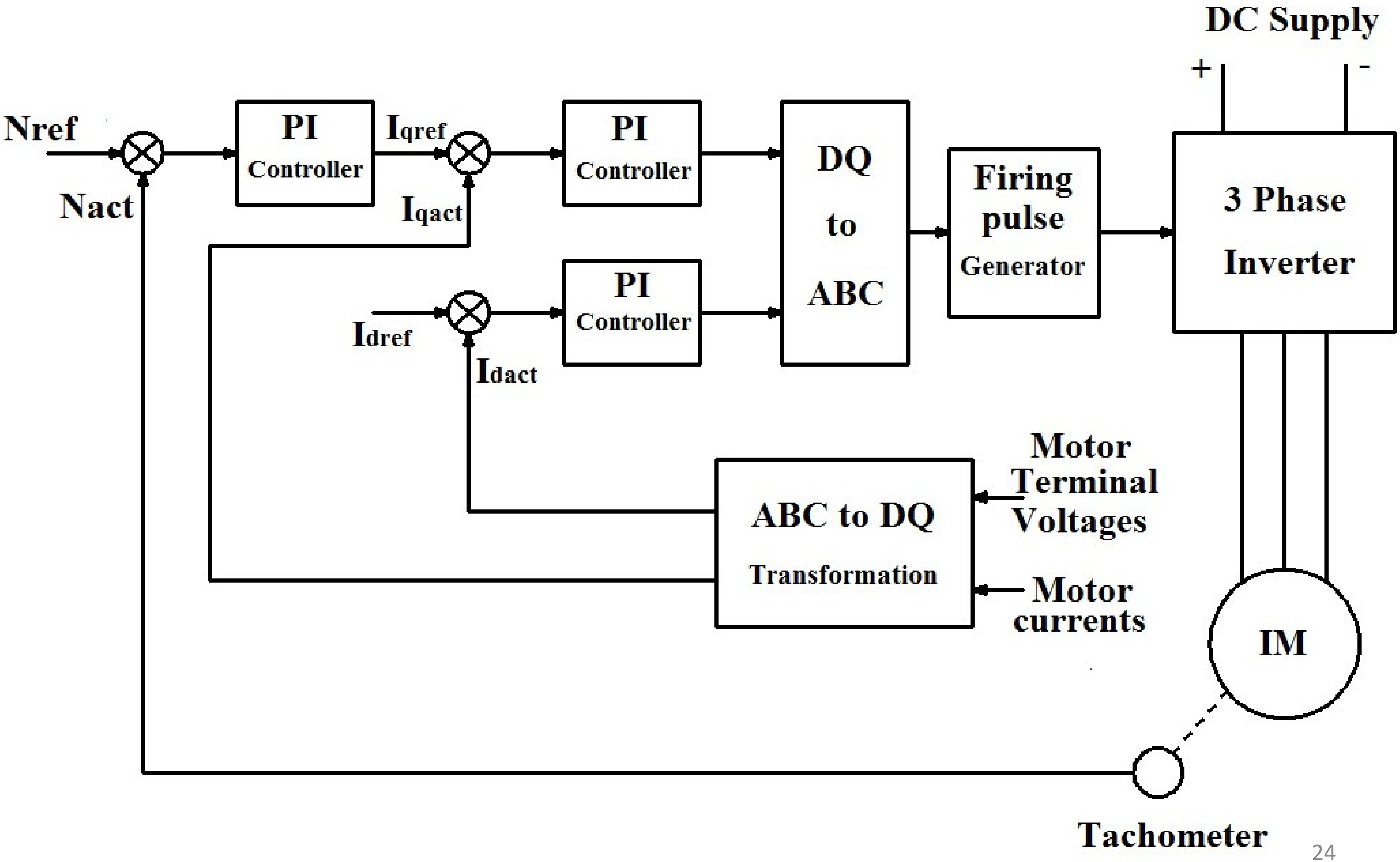
- To control torque & flux independently, we transform the 3 phase stator currents (I_a, I_b & I_c) into 2 phase current by using ABC to dq transformation (Clarke & Park transformations)
- Now the 2 phase currents are

  1. Flux producing component, i_d – which produces the net flux in the motor
  2. Torque producing component, i_q – which produces the torque in the motor

- There are 2 type of vector control

1. Direct vector control
   - here the actual speed of the motor is sensed by using a tachometer
2. Indirect vector control
   - here the actual speed is calculated from machine terminal voltages & no tachometers are used

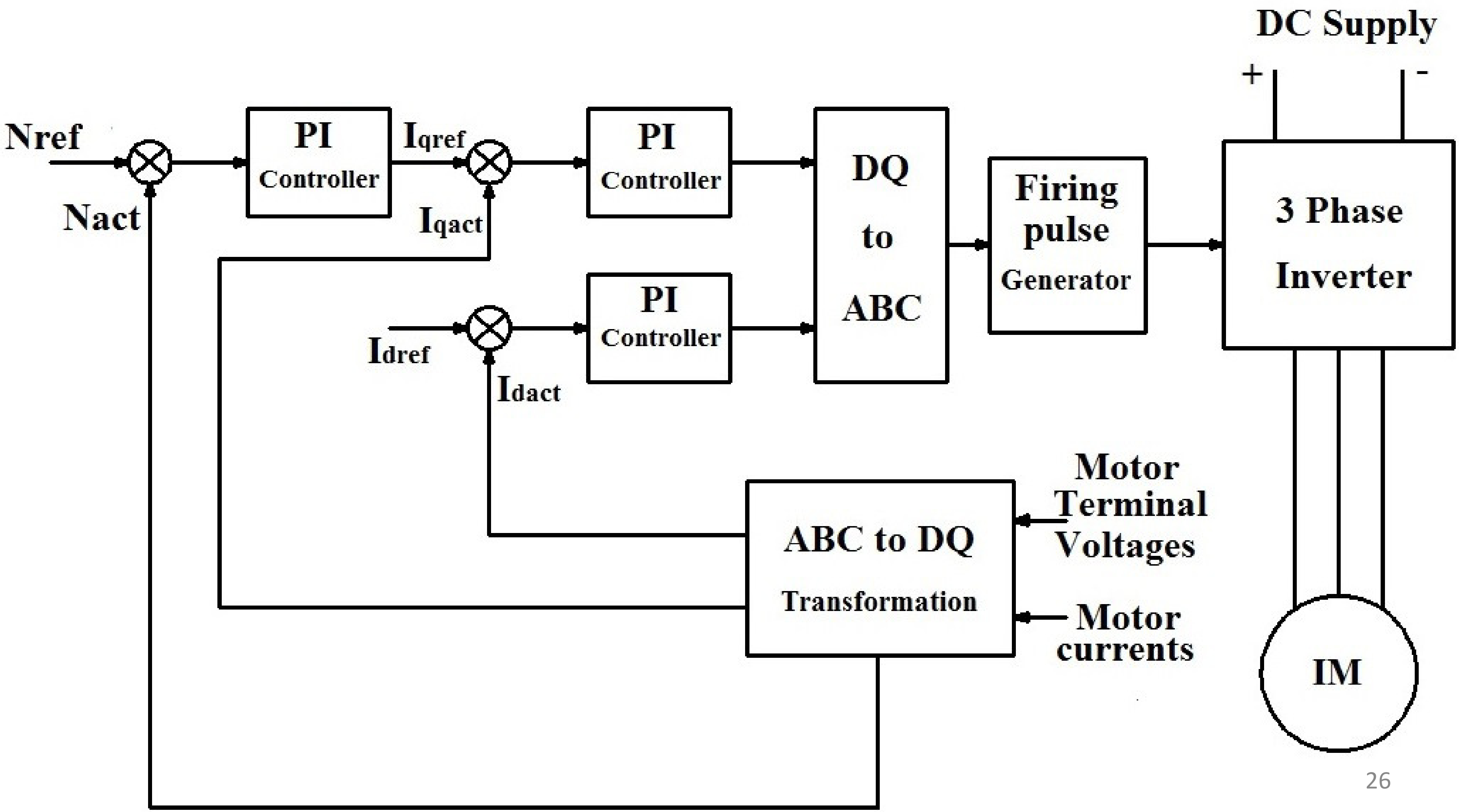
1. Direct vector control



- Here the actual 3 phase motor terminal voltages & currents are sensed & they are converted to 2 phase frame to get the actual values of torque producing & flux producing components of stator current
- The actual motor speed is sensed by a tachometer & is compared with reference speed to get speed error
- The error is processed by using a PI controller & its output is the reference torque producing component of stator current (I_{qref})
- The I_{qref} is compared with I_{qact} & the error is processed by using a PI controller
- The output of PI controller is given to DQ to ABC transforming block
- The reference flux current (I_{dref}) is compared with actual (I_{dact}) to get error & is processed by using PI controller
- The output of controller is given to DQ to ABC transforming block
- The DQ to ABC transforming block will generate the three phase currents which will produce the desired flux & torque inside the machine. The firing pulse generator will produce the firing pulses for inverter switches

- When inverter switches operates based on the generated firing pulses, the inverter output will be such that to get desired torque & flux in the machine

2. Indirect vector control



Transformations in reference frame theory

Need of transformations

- The analysis of 3 phase electrical circuits are complicated since it involve 3 time varying quantities (3 phase ABC reference frame)
- In 2 phase, there is only 2 time varying quantities, so the analysis is less complicated (2 phase αβ reference frame)
- If the quantities are not time varying, then analysis become simpler (2 phase dq reference frame)
- So we go for transformations in complex poly phase circuit analysis
- The process of replacing one set of variables to another related set of variables is called ***transformations***
- The ***general form of transformation equations*** is

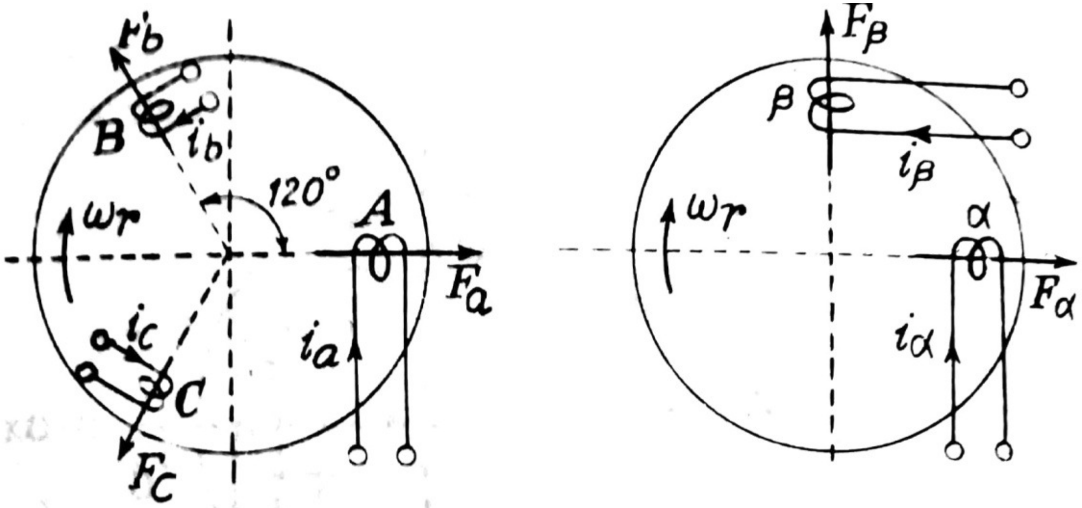
  [New variables] = [Transformation matrix][Old variables]

  [Old variables] = [Inverse transformation matrix][New variables]
- Transformation matrix is a matrix containing the coefficients that relates new & old variables

ABC to αβ transformation (Clarke transformation)

(3 phase rotational reference frame to 2 phase rotational reference frame)

- Let i_a,i_b & i_c be the 3 phase currents & i_α and i_β represents 2 phase currents



- Now the transformation equations are given by

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

- This transformation is applicable for voltages also

αβ to ABC transformation (Inverse Clarke transformation)

(2 phase stationary reference frame to 3 phase rotational reference frame)

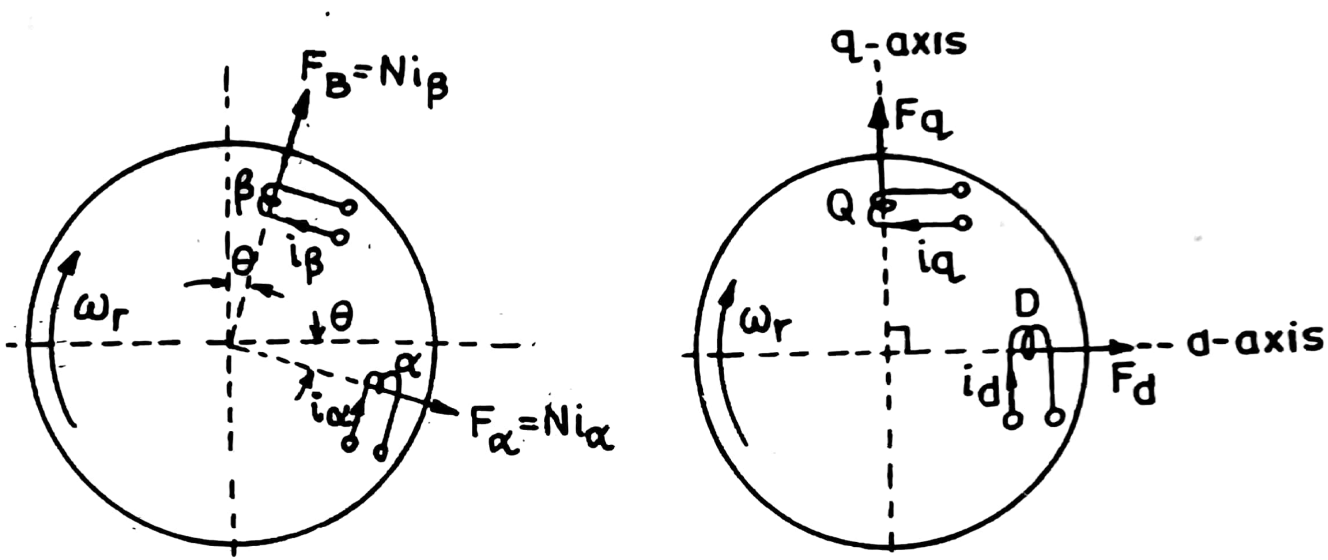
- Let i_α and i_β represents 2 phase currents & i_a,i_b & i_c be the 3 phase currents
- Now the transformation equations are given by

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}$$

- This transformation is applicable for voltages also

αβ to dq transformation

(2 phase rotational reference frame to 2 phase stationary reference frame)



- The transformation equations are given by

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}$$

dq to αβ transformation

(2 phase stationary reference frame to 2 phase rotational reference frame)

- The transformation equations are given by

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}$$

Concept of space vector

- Space vector is a transformation for analyzing three-phase electric systems.
- The term “space” originally stands for the two-dimensional complex plane, in which the three-phase quantities are transformed
- The transformation from 3 phase to 2 phase is called space vector transformation

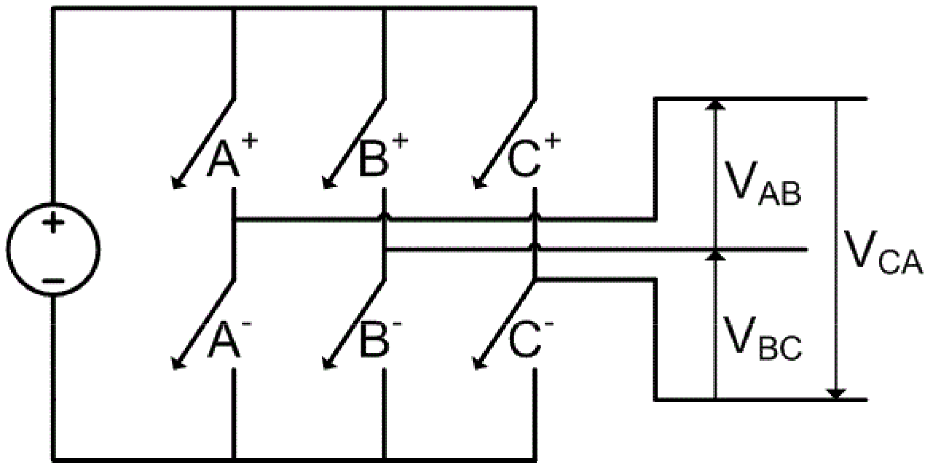
- The 3 phase voltages, currents and fluxes of AC motors can be analyzed in terms of complex space vectors
- With regard to current, space vector can be defined as follows
- Let i_a, i_b, i_c be the instantaneous currents in the stator phases, then the stator current vector i_s is given by
- $i_s = i_a + \alpha i_b + \alpha^2 i_c$

Where $\alpha = 1 < 120$ ($e^{j(2\pi/3)}$), $\alpha^2 = 1 < 240$ ($e^{j(4\pi/3)}$)

Space vector modulation

- It is an algorithm for the control of pulse width modulation (PWM)
- It is used for the creation of alternating current (AC) waveforms, most commonly to drive 3 phase AC powered motors at varying speeds from a DC source
- Consider a 3 phase inverter as shown in figure
- The output may be given to a 3 phase induction motor
- The switches must be controlled so that at at no time are both switches in the same leg turned & cause a short circuit of the DC supply

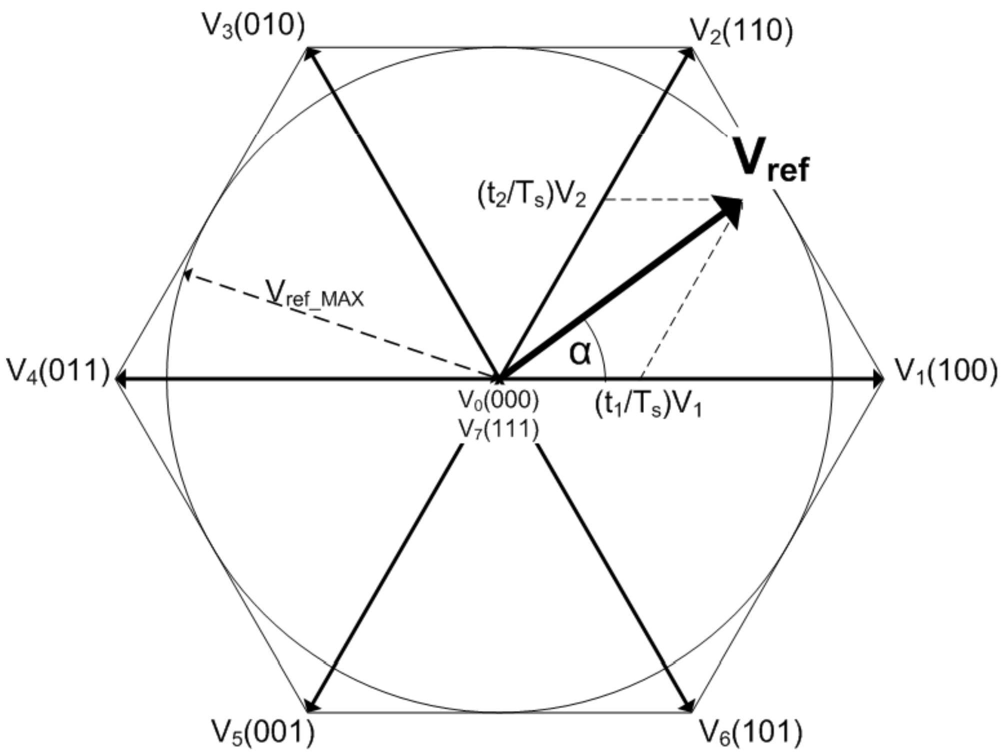
- This requirement may be met by the complementary operation of the switches within a leg. i.e. if A^+ is on then A^- is off and vice versa.



- This leads to eight possible switching vectors for the inverter, V_0 through V_7 with six active switching vectors and two zero vectors

Vector	A^+	B^+	C^+	A^-	B^-	C^-	V_{AB}	V_{BC}	V_{CA}	
V_0 = {000}	OFF	OFF	OFF	ON	ON	ON	0	0	0	zero vector
V_1 = {100}	ON	OFF	OFF	OFF	ON	ON	$+V_{dc}$	0	$-V_{dc}$	active vector
V_2 = {110}	ON	ON	OFF	OFF	OFF	ON	0	$+V_{dc}$	$-V_{dc}$	active vector
V_3 = {010}	OFF	ON	OFF	ON	OFF	ON	$-V_{dc}$	$+V_{dc}$	0	active vector
V_4 = {011}	OFF	ON	ON	ON	OFF	OFF	$-V_{dc}$	0	$+V_{dc}$	active vector
V_5 = {001}	OFF	OFF	ON	ON	ON	OFF	0	$-V_{dc}$	$+V_{dc}$	active vector
V_6 = {101}	ON	OFF	ON	OFF	ON	OFF	$+V_{dc}$	$-V_{dc}$	0	active vector
V_7 = {111}	ON	ON	ON	OFF	OFF	OFF	0	0	0	zero vector

- To implement space vector modulation, a reference signal (V_{ref}) may be generated
- The reference vector is then synthesized using a combination of the two adjacent active switching vectors and one or both of the zero vectors



Advantages of Space vector PWM

- Harmonics in output voltage decreases
- Output voltage increases
- Switching losses decreases
- Smooth control of output voltage and frequency

Module VI

Speed control of synchronous motor drives

Synchronous motor

- A synchronous motor is constructionally same an alternator
- It runs at synchronous speed or it remains stand still
- Speed can be varied by varying supply frequency because synchronous speed, $N_s = (120f/p)$
- Due to unavailability of economical variable frequency sources, this method of speed control was not used in past & they were mainly used for constant speed applications
- The development of semiconductor variable frequency sources such as inverter & cycloconverter allowed the use of synchronous motor in variable speed applications
- It is not self starting. It has to be run upto near synchronous speed by some means & it can be synchronised to supply
- Starting methods : a) using an auxiliary motor

  b) using damper windings

Types of synchronous motors

- Commonly used synchronous motors are
  1. Wound field synchronous motor (Cylindrical & salient pole)
  2. Permanent magnet synchronous motor
  3. Synchronous reluctance motor
  4. Hysteresis motor
- All these motors have a stator with 3 phase winding which is connected to an AC source
- Fractional horse power synchronous reluctance & hysteresis motors employ a 1 phase stator

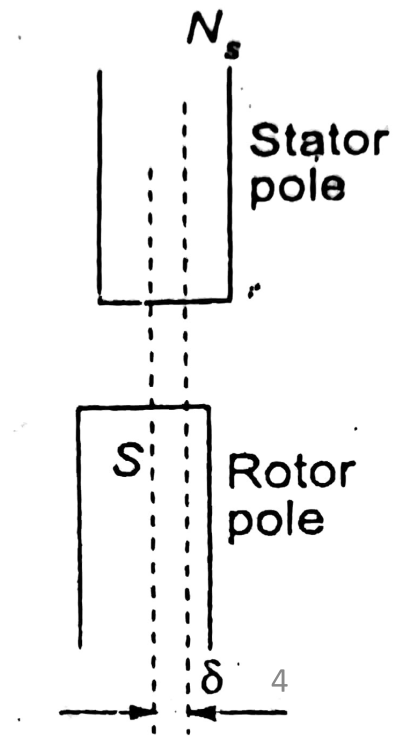
Operation of a wound field synchronous motor

- Rotor is provided with a DC field winding & damper windings
- Stator contain 3 phase winding & is connected to AC supply
- Stator produce the same number of poles as DC field produces
- When a 3 phase supply is given to stator, a rotating magnetic field revolving at synchronous speed is produced
- The DC excitation in rotor produces a field
- This field interacts with rotating magnetic field to produce a torque which is pulsating in nature & not unidirectional

- As a result synchronous motor is not self starting
- Normally the motor is made self starting by providing damper windings on rotor
- Due to the presence of damper windings, motor will start as an induction motor
- When speed of motor reaches near synchronous speed, DC excitation is given to rotor
- Now the rotor poles gets locked with rotating magnetic field poles in stator & continue to rotate at synchronous speed

<u>Load angle/power angle/torque angle (δ)</u>

- The rotor poles are locked with stator poles & both run at synchronous speed in same direction
- As load on motor increases, the rotor tends to fall back in phase by some angle
- This angle is known as load angle (δ)
- The value of δ depends upon the load



Pull out torque

The power produced by synchronous motor, $P_m = \frac{3VE}{X_s} Sin\delta$

Where, V = stator supply voltage

E = Field excitation voltage

Torque, $T = \frac{P_m}{\omega_s} = \frac{3VE}{\omega_s X_s} Sin\delta$

For a given value of supply voltage, frequency & field excitation, the torque will be maximum when δ = 90

i.e, $T_{\max} = \frac{3VE}{\omega_s X_s}$

- The maximum torque is known as *pull out torque*
- Any increase in torque beyond this value will cause the motor to slow down & the synchronism is lost
- This phenomenon is called *pulling out of step*

Variable frequency control of Synchronous motor

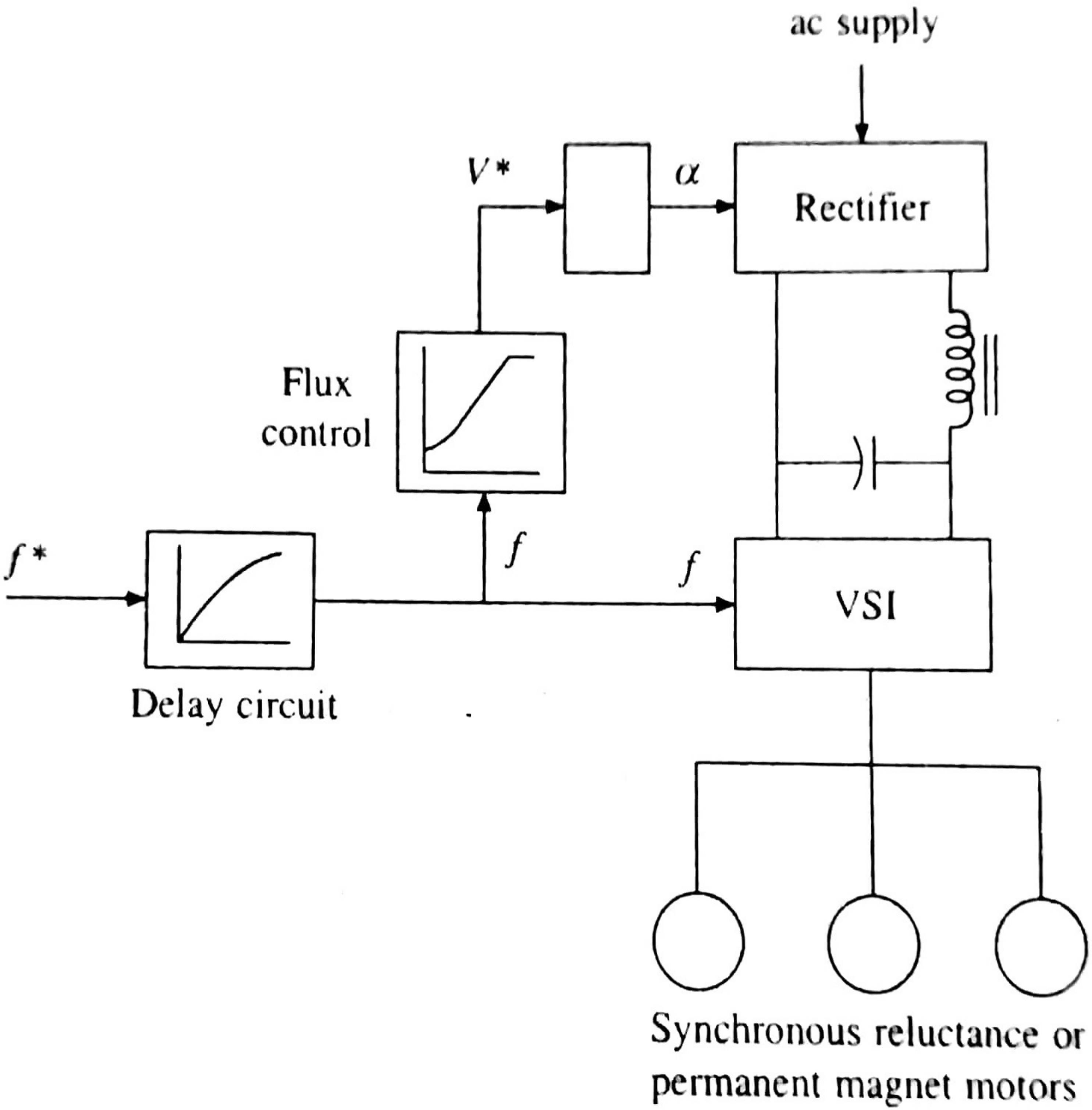
- Synchronous speed α frequency
- So by varying frequency, speed can be controlled
- Like in induction motor, upto base speed, the V/f ratio is kept constant & for speed above base speed, the terminal voltage is maintained at rated value & frequency is varied
- In variable frequency control, synchronous motor may operate in two modes

  a) True synchronous mode /open loop mode

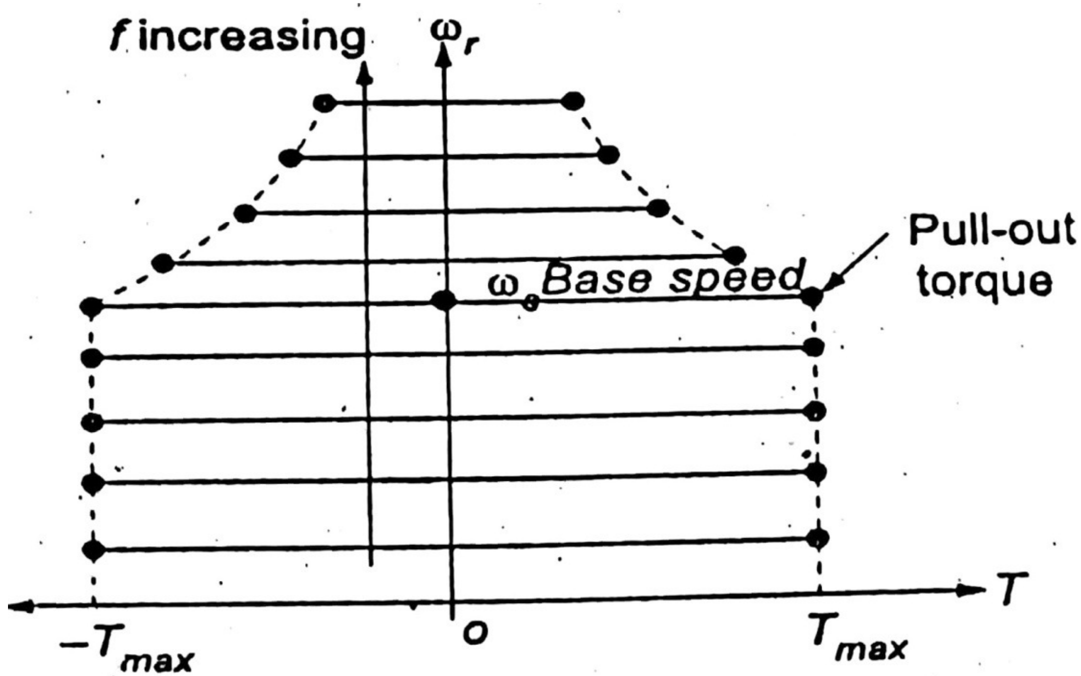
  b) Self controlled mode

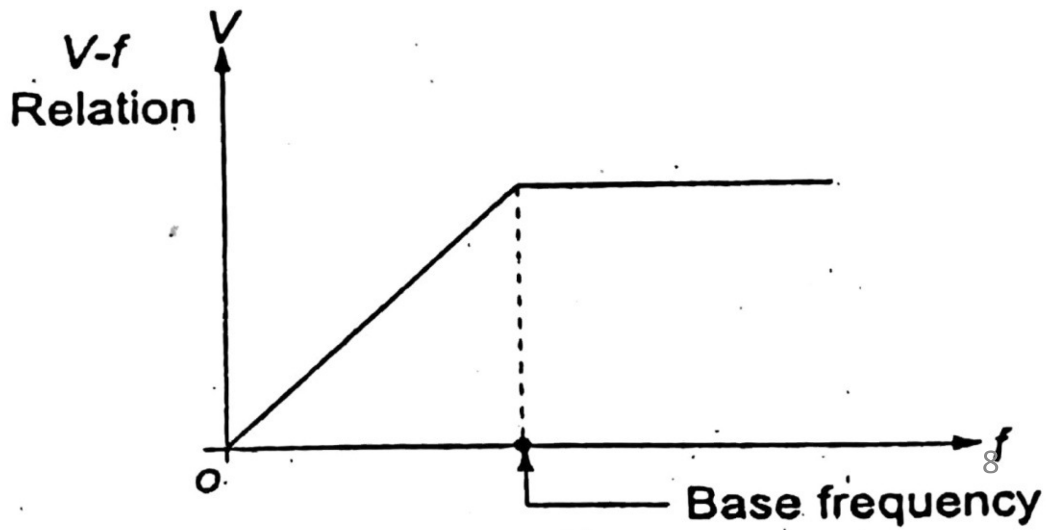
a) <u>True synchronous mode</u>

- Here the stator supply frequency is controlled from an independent oscillator
- Frequency from initial value to desired value is varied gradually so that the difference between synchronous speed & actual speed is always small


ac supply
V*
α
Rectifier
Flux
control
f
f*
f
VSI
Delay circuit
Synchronous reluctance or
permanent magnet motors

- A drive operating in true synchronous mode is shown in previous slide
- Frequency command f* is applied to a VSI through a delay circuit so that rotor speed is able to track the changes in frequency
- A flux control block changes stator voltage with frequency to maintain a constant flux below base speed & constant terminal voltage above base speed





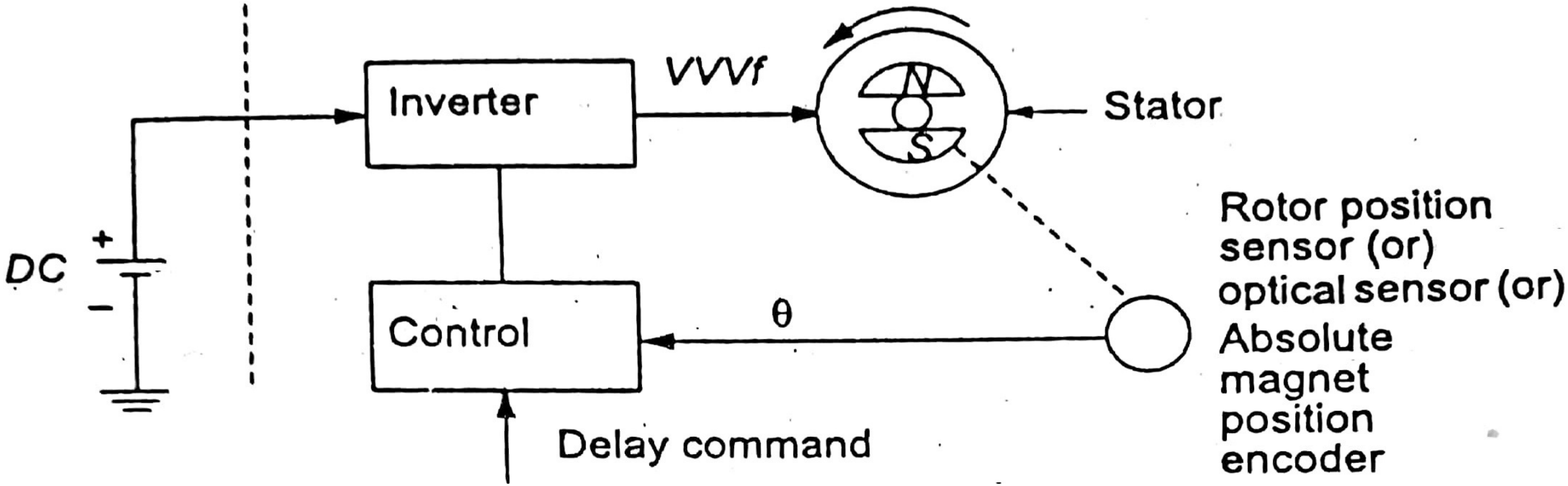
- Under steady operating conditions, a gradual increase in frequency causes the synchronous speed > actual speed & torque angle δ increases
- To follow this change in frequency, motor accelerates & settles at new speed after hunting oscillations which are damped by damper windings
- A gradual decrease in frequency causes the synchronous speed to become < actual speed & δ become negative
- To follow this change in frequency, the motor decelerates under regenerative braking
- Motor settles down at new speed after hunting oscillations
- The frequency must be changed gradually to allow the rotor to track the changes in revolving field, otherwise the motor may pull out of step
- This method is employed only in multiple synchronous motor drives requiring accurate speed tracking between motors
- E.g, fibre spinning mills, paper mills, textile mills

b) Self controlled mode

- A machine is said to be in self controlled mode if it gets its variable frequency from an inverter whose thyristors are fired in a sequence, using the information of rotor position or stator voltages

i) Rotor position sensor

- here a rotor position sensor is used, which measures the rotor position w.r.to stator & sends pulses to thyristor
- Hence the frequency of inverter output is decided by rotor speed
- Here the supply frequency is changed so that the synchronous speed is same as rotor speed & hence rotor cannot pull out of slip & hunting oscillations are eliminated
- A self controlled motor has properties of a DC machine both under steady state & dynamic conditions
- There fore it is called a commutator less motor



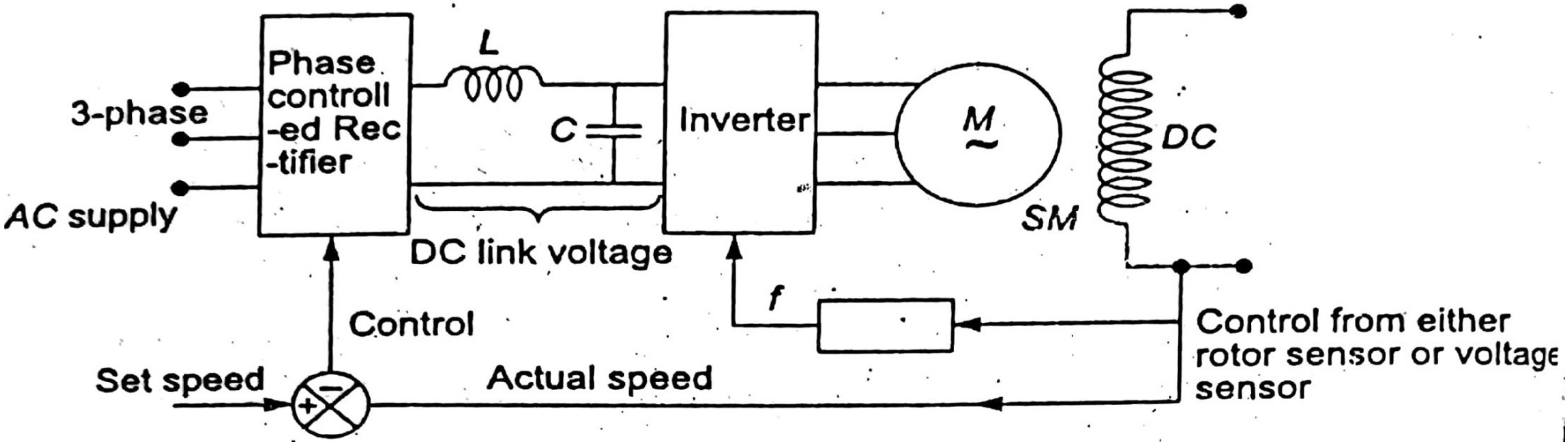
ii) *Stator voltage sensor*

- Here the firing pulses for inverter switches are derived from stator induced voltages (stator induced voltages depends on rotor position)
- The synchronous machine with the inverter can be considered to be similar to a line commutated converter where the firing pulses are synchronised with the line voltage
- Variable speed synchronous motor drives are generally operated in self controlled mode

VSI fed Synchronous Motor Drives

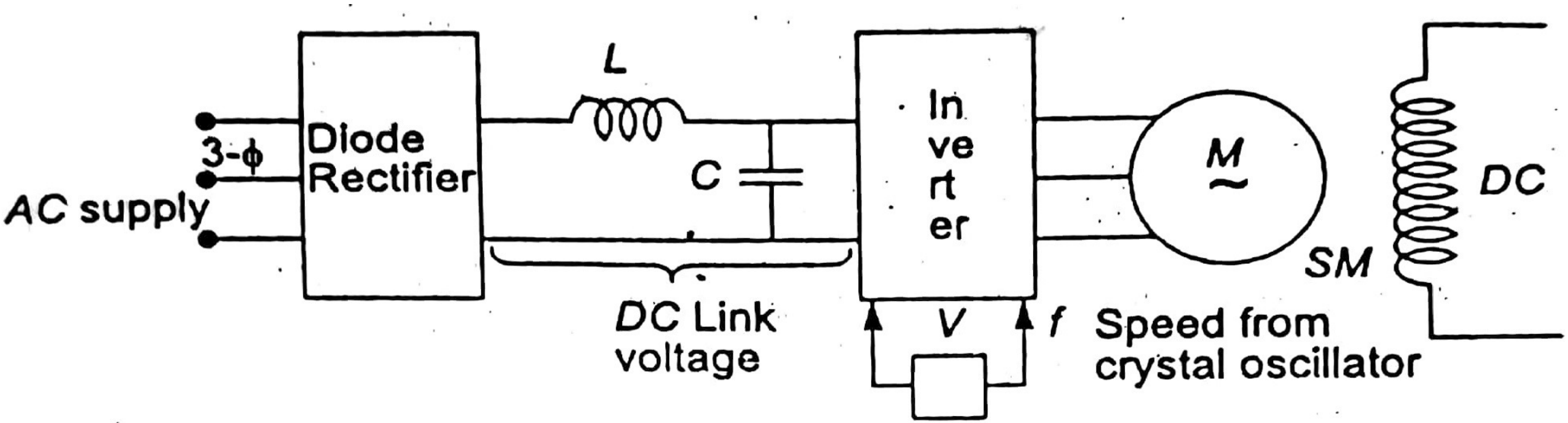
- VSI fed synchronous motor drives can be classified as

1. **Self control mode using a rotor position sensor or stator voltage sensor**



- Here the output frequency is controlled by the inverter & voltage is controlled by the controlled rectifier
- If the inverter is PWM inverter, both frequency & voltage can be controlled within the inverter
- Upto base frequency, V/f ratio is kept constant & above base speed f is varied by keeping V at rated value

2. **True synchronous mode where the speed of motor is determined by the external independent oscillator**



- Here the output frequency & voltage is controlled within the PWM inverter
- If the inverter is not PWM controlled, then the voltage is controlled by using a controlled rectifier & frequency is controlled by the inverter

Advantages & drawbacks of True synchronous mode operation

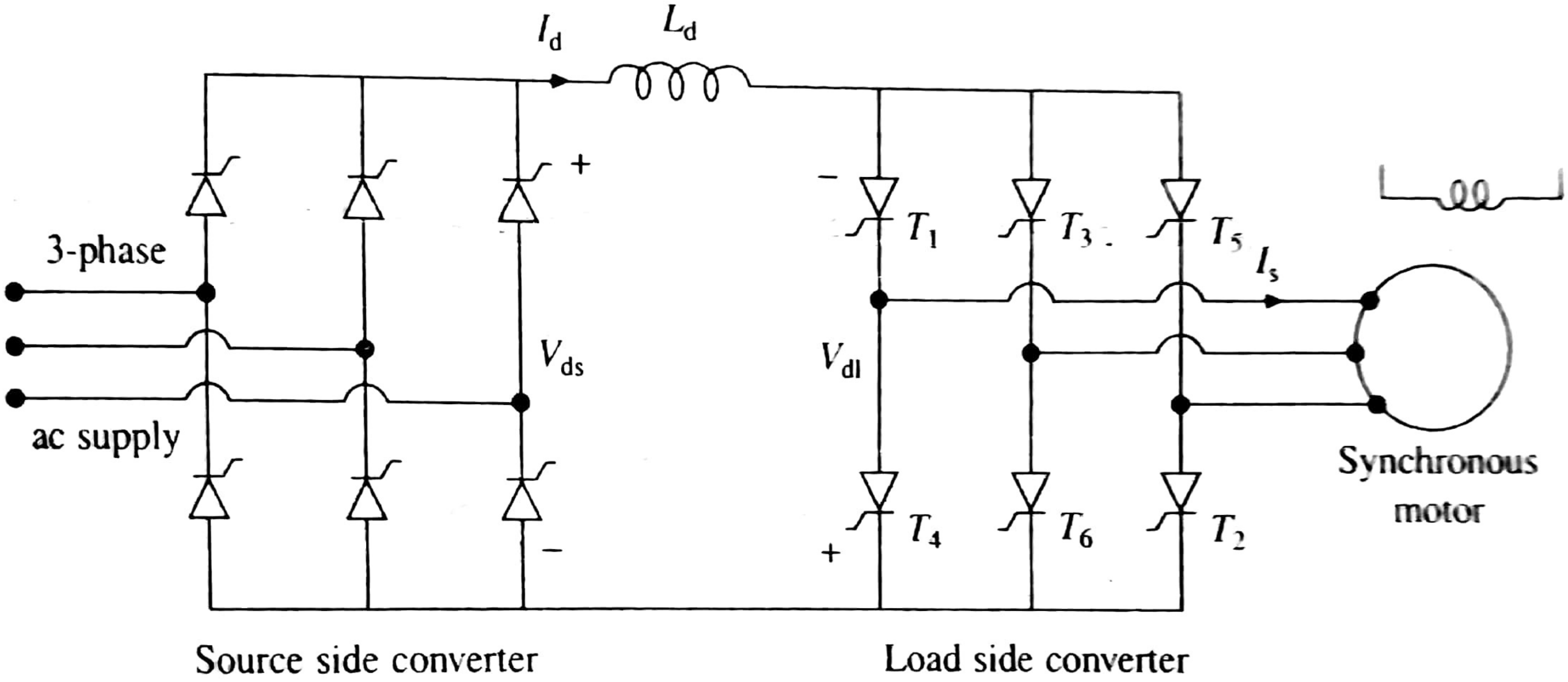
- Multi motor drive is possible
- Involve hunting & stability problems
- Can be implemented by using VSI & CSI
- Power factor can be controlled in a wound field synchronous motor by controlling the field excitation

Advantages & drawbacks of Self controlled mode operation

- Eliminates hunting & stability problems
- Good dynamic response
- Can be implemented by using VSI & CSI
- Load commutation of inverter is possible & no need of forced commutation
- Power factor can be controlled in a wound field synchronous motor by controlling the field excitation

Self controlled synchronous motor drive employing a load commutated thyristor inverter

- A CSI fed synchronous motor drive may employ a load commutated thyristor inverter
- When a synchronous motor is fed from a CSI, it can be operated in self controlled mode or true synchronous mode
- When fed from CSI, synchronous motor is operated at leading power factor so that the inverter will work as a load commutated inverter
- A load commutated inverter fed synchronous motor under self controlled mode is shown in figure
- The source side converter is a 6 pulse line commutated thyristor converter
- For a firing angle range $0<\alpha_s<90$, it works as a line commutated fully controlled rectifier delivering positive V_d & I_d
- For a firing angle range $90<\alpha_s<180$, it works as a line commutated inverter delivering negative V_d & I_d



- When synchronous motor is operated at leading power factor, thyristors of load side converter can be commutated by motor induced voltages in the same way, as thyristors of a line commutated converter are commutated by line voltages
- Commutation of thyristors by induced voltages of load is known as load commutation
- The load side converter will work as an inverter for $90<\alpha_L<180$
- For $0<\alpha_L<90$, it work as a rectifier

Motoring operation – for $0<\alpha_S<90$ & $90<\alpha_L<180$, source side converter works as rectifier & load side converter as inverter causing power to flow from AC source to motor

Generating operation - for $90<\alpha_S<180$ & $0<\alpha_L<90$, load side converter work as rectifier & source side converter as inverter causing power to flow from motor to AC source

- The DC link inductor L_d reduces ripples in the DC link current
- Due to L_d, load side converter works as a CSI
- For operating in self controlled mode, rotating magnetic field speed should be same as rotor speed
- This condition is achieved by making the frequency of load side converter output voltage equal to frequency of voltage induced in the armature
- Normally hall sensors are used to obtain rotor position information
- The difference between CSI fed induction motor drive & synchronous motor drive is that induction motor drive uses forced commutation & synchronous motor drive uses load commutation

Advantages

- High efficiency
- Four quadrant operation is possible with regenerative braking
- Higher power rating (upto 100MW)
- Ability to run at higher speeds (6000 rpm)

Permanent magnet synchronous motor drives

- In a permanent magnet synchronous motor, the DC field winding in rotor is replaced by a permanent magnet
- *Advantages of using a permanent magnet are*

  * Elimination of field copper loss
  * Higher power density
  * lower rotor inertia
  * more robust construction of rotor
  * higher efficiency

- *Drawbacks of using permanent magnets are*

  * Loss of flexibility in field flux control
  * Demagnetization effect
  * Higher cost

Permanent magnet materials

- Commonly used materials for permanent magnets are
  * Alnico
  * Ferrite
  * Cobalt-Samarium
  * Neodymium-Iron-Boron
  * Barium and Strontium ferrites

Construction

- The main parts are stator & rotor
- Stator contain a 3 phase winding placed in stator slots
- Rotor contain permanent magnets

Based on construction of rotor, permanent magnet synchronous motors are classified into 2

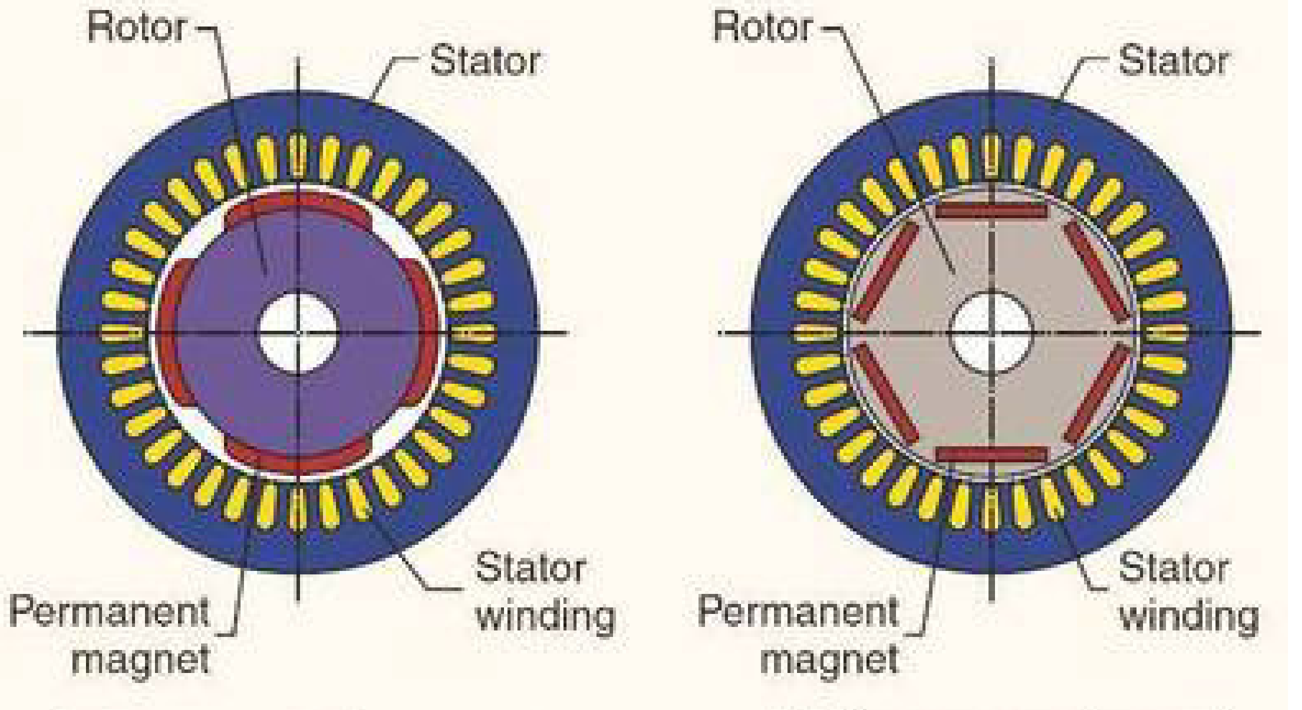
1. **Surface mounted permanent magnet motor**

- Here the permanent magnets are mounted on the surface of rotor

- Permanent magnets are glued on the rotor surface using epoxy adhesive
- Rotor has an iron core which is made up of laminations
- Since the rotor is having a salient pole structure, this motor is not used for high speed applications

2. **Interior permanent magnet motor**

- Here the permanent magnets are placed inside the slots in rotor



Surface mounted permanent magnet motor (SPM).

Interior permanent magnet motor (IPM).

- Since the permanent magnets are placed inside the rotor, rotor is having a non salient pole structure
- So this motor is used for high speed applications

Types of permanent magnet synchronous motor drive

- Based on the nature of voltage induced in stator, the motor is classified into
  1. Sinusoidal PMAC motor
  2. Trapezoidal PMAC motor (Brushless DC motor)
- The speed of PMAC motors are controlled by feeding them from variable frequency voltage/current source inverter
- They are operated in self controlled mode
- Rotor position sensors are employed for operation in self control mode
- Alternatively stator induced voltages can be used to achieve self control
- MOSFET inverters are used for low voltage & power applications and IGBT inverters are used for high voltage & power applications

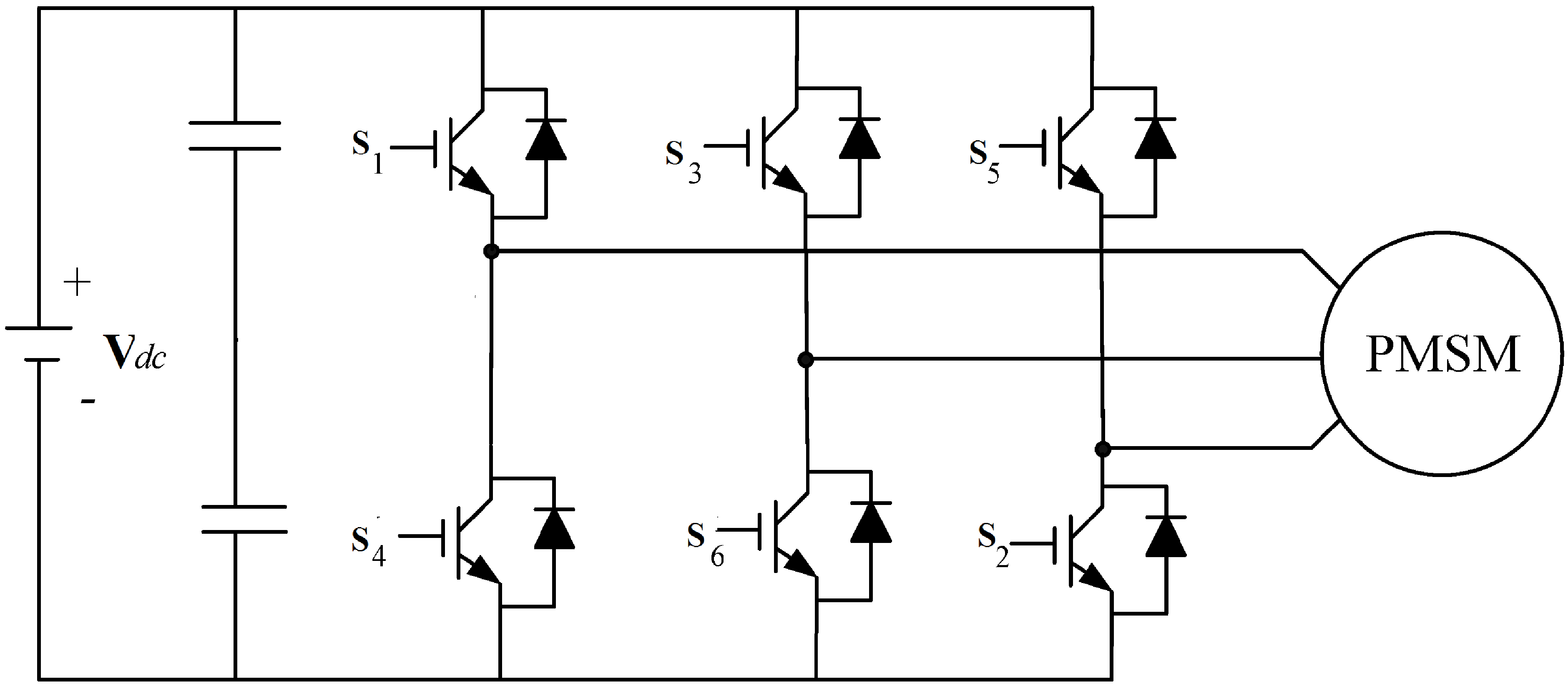
1. Sinusoidal Permanent Magnet AC motor

- Here the stator carries a 3 phase winding which is sinusoidally distributed in stator slots
- The stator windings are excited from a 3 phase supply to produce a rotating magnetic field
- The rotor contain permanent magnets (interior or surface mounted) embedded in the steel rotor to create a constant magnetic field
- The rotor poles are so shaped that the voltage induced in a stator phase has a sinusoidal wave shape
- A Permanent magnet AC motor is not self starting like a wound field synchronous motor
- Here we can't use damper windings on rotor to make the motor self starting
- These motors require a variable frequency AC source for starting

Speed control of sinusoidal permanent magnet AC motor

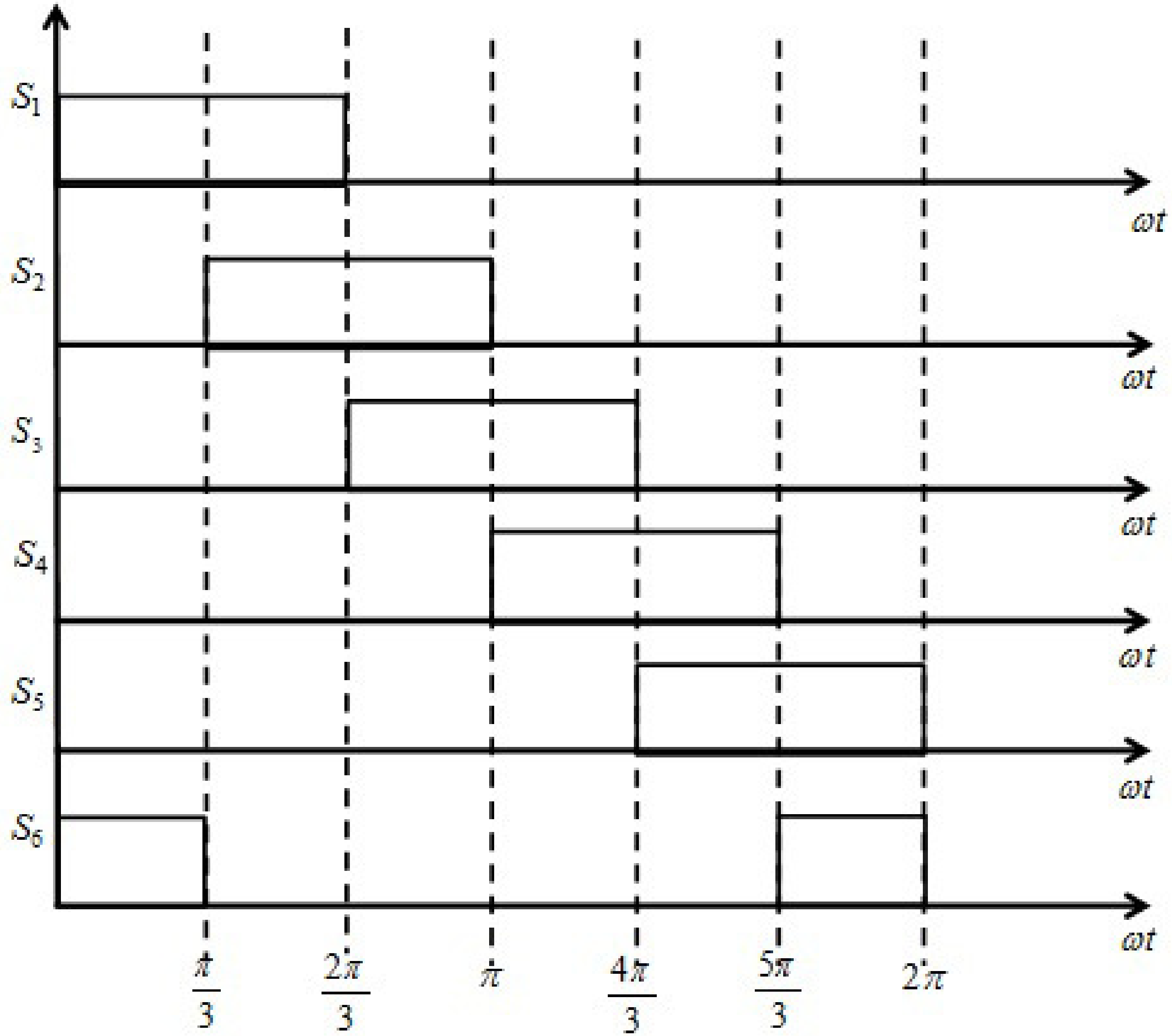
- The speed of the motor can be varied by changing the stator supply frequency
- For speed control below base speed, v/f ratio is kept constant

- For speed control above base speed, voltage is kept at maximum rated value & frequency is varied (field weakening operation)
- Permanent magnet AC motors are fed from variable voltage variable frequency inverters
- The inverter switches are fired according to the rotor position information
- The inverter can operate in 120/180 degree conduction mode



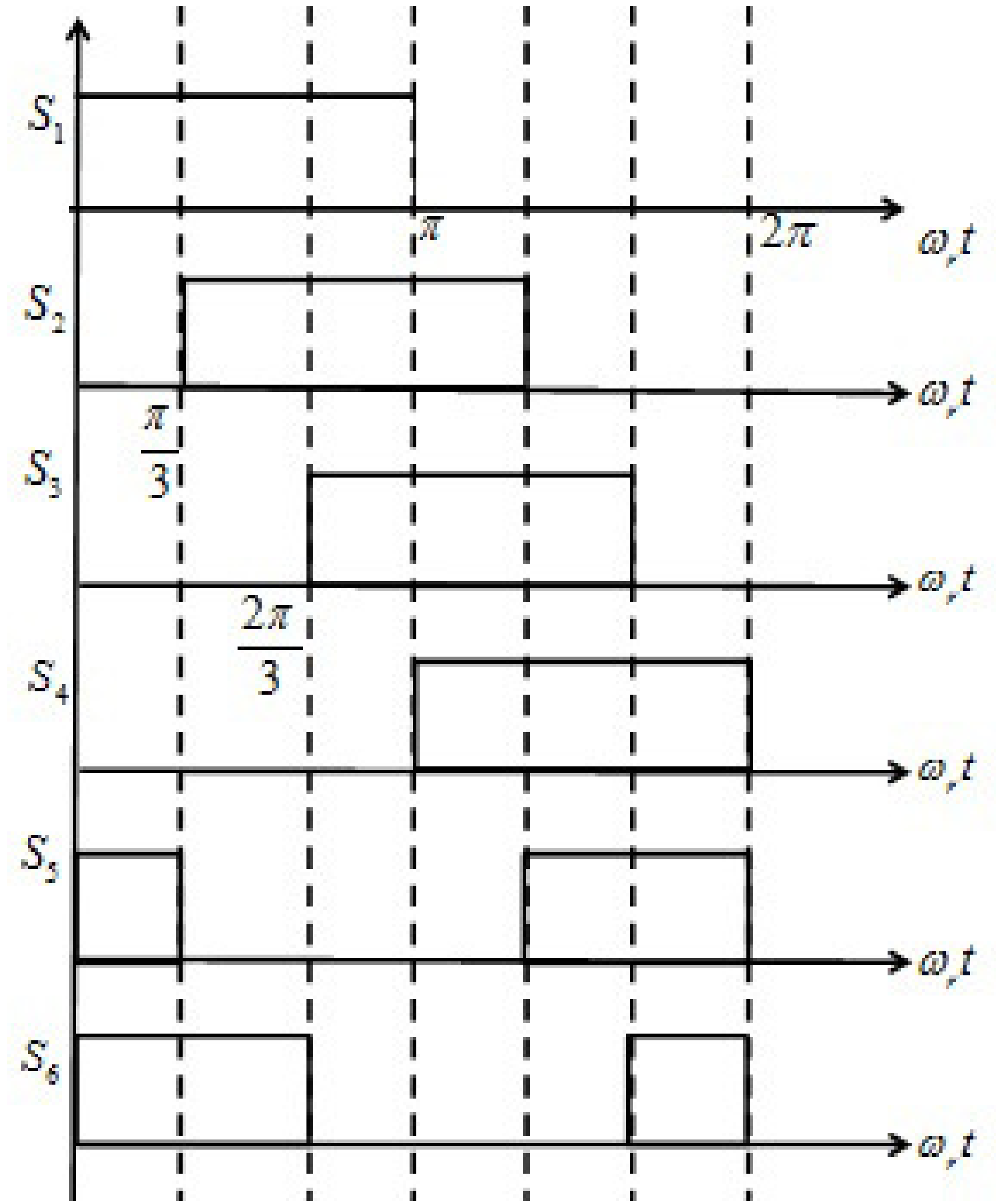
120 degree conduction mode

- Here at any given point of time, only two switches conduct and six switching combinations are possible
- The gating signals are shown below



180 degree conduction mode

- Here at any point of time, at least three switches are on.
- The gating sequence for this mode of operation is shown below



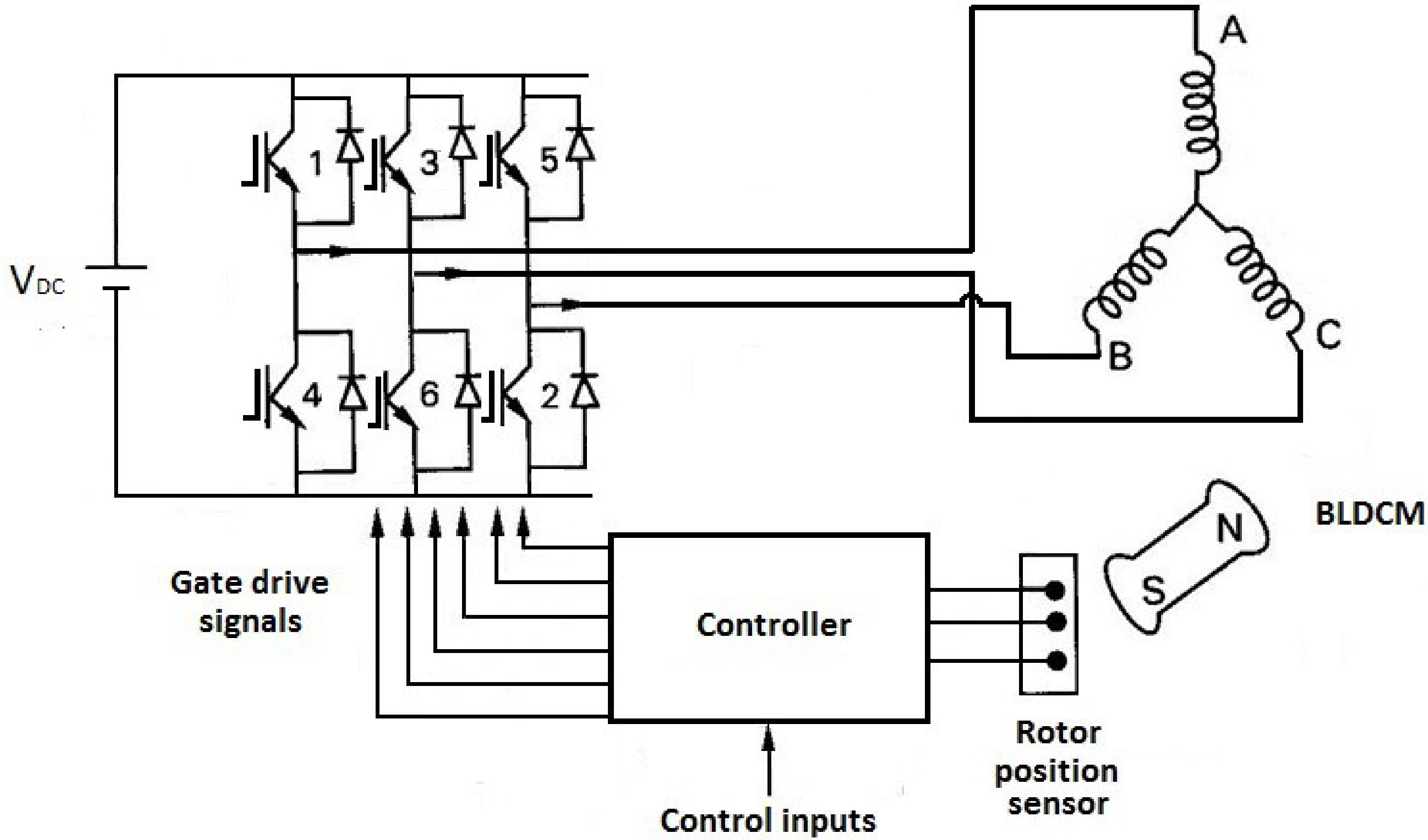
2. Trapezoidal PMAC motor

- This motor is also known as ***BLDC motor***
- Here the stator carries a 3 phase concentrated winding
- Rotor contain permanent magnets with wide pole arc so that the stator induced voltages are trapezoidal in shape
- BLDC motor is supplied from an inverter
- This motor operates only in self control mode, i.e, rotor position information is required for operation
- The rotor position information is obtained by using hall sensors or from stator terminal voltages

Working

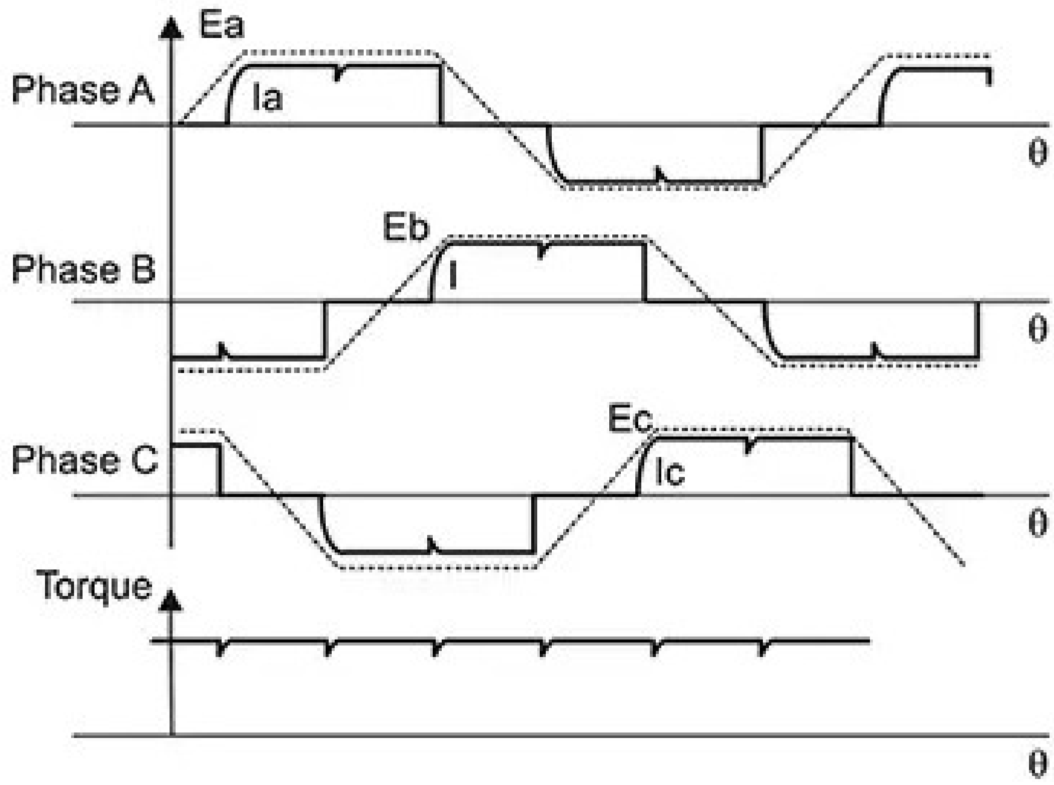
- The motor is supplied from an inverter
- The inverter switches are turned ON/OFF in a sequence to ensure proper commutation
- Here two phases are energized at any instant
- Permanent magnets create rotor flux and energized stator windings create electromagnetic poles
- The rotor is attracted by the energized stator poles

- By using an appropriate sequence to supply the stator phases, a rotational field on stator is created and maintained
- Now the rotor poles follow the stator rotating magnetic field poles
- Here stator is having concentric winding, so induced emf (back emf) is trapezoidal in nature



- Here two switches are ON at any instant, so that two phases are energized
- Each switch conducts for 120 degree
- The switching sequence and waveforms are shown below

Transistor \ Step	①	②	③	④	⑤	⑥
Tr1	ON					ON
Tr2		ON	ON			
Tr3				ON	ON	
Tr4			ON	ON		
Tr5					ON	ON
Tr6	ON	ON				
Phase U	N	—	S	S	—	N
Phase V	—	N	N	—	S	S
Phase W	S	S	—	N	N	—



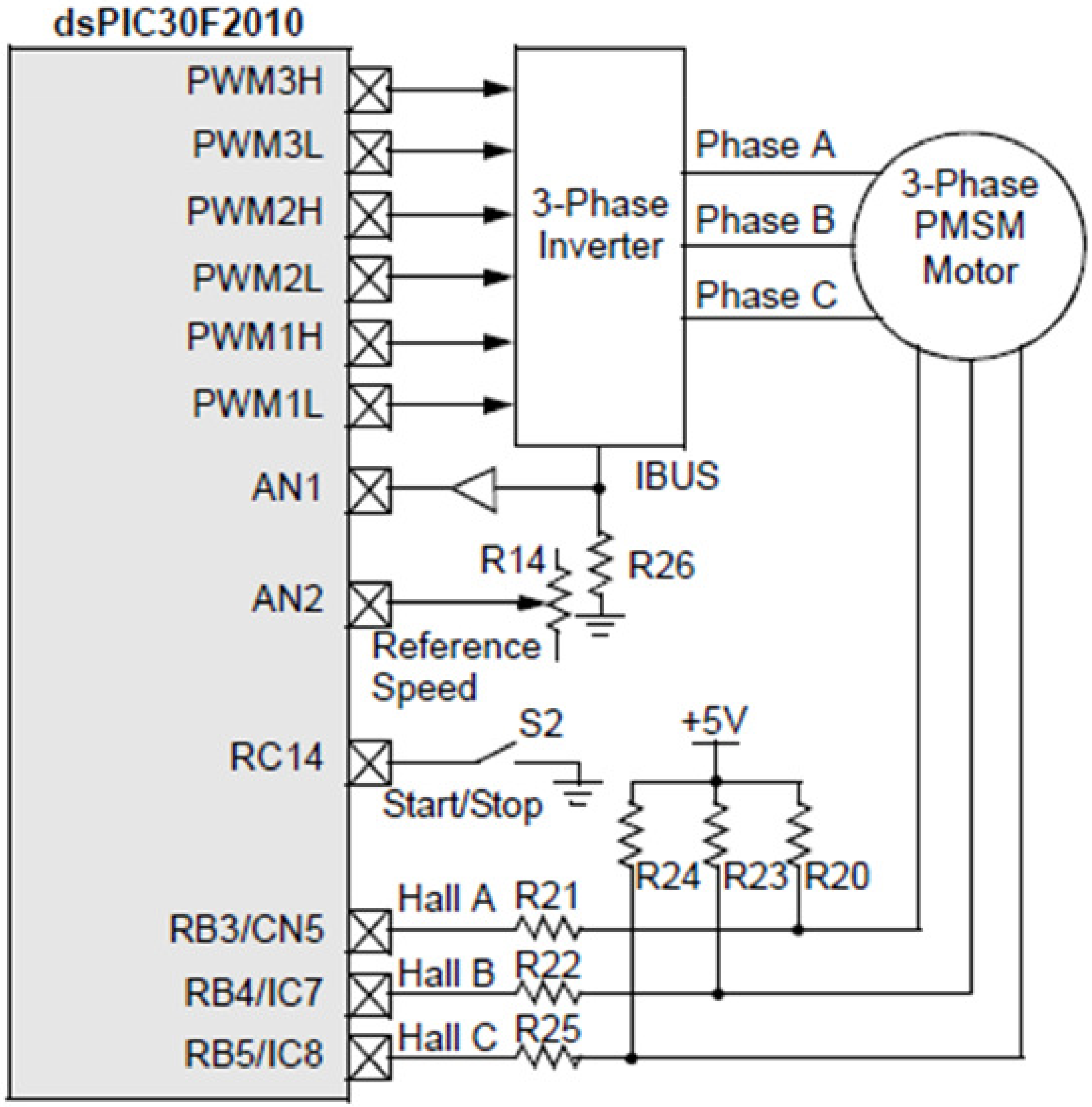
- A trapezoidal PMAC motor is similar to a DC motor without commutator and brushes
- Like a DC motor, here the voltage induced in stator is proportional to speed and torque is proportional to current
- The stator and rotor magnetic fields remain stationary with respect to each other
- In BLDC motor the commutation is electronic commutation, achieved by proper switching of inverter switches

Comparison of Sinusoidal & Trapezoidal PMAC motor

Trapezoidal PMAC	Sinusoidal PMAC
Synchronous machine	Synchronous machine
Trapezoidal back emf	Sinusoidal back emf
Stator flux position changes at every 60 degree	Continuous stator flux position variation
Only two phases energised at any instant	Three phases are energised at any instant
Torque ripple at commutation	No torque ripple at commutation
Low order current harmonics at audible range	Less harmonics due to sinusoidal excitation
Higher core losses due to harmonic content	Lower core loss
Less switching losses	Higher switching losses
Control algorithm is simpler	Control algorithm is complicated

Microcontroller based Permanent magnet Synchronous motor drive

- The schematic diagram of a microcontroller controlled permanent magnet synchronous motor drive is shown below



- dsPIC16F2010 is a 16 bit microcontroller
- 28 pin configuration
- Default 6 PWM output channels
- RB3, RB4 & RB5 are I/O ports. Here they are used to give the hall sensor output signals to the controller
- RC14 is digital input port, used to give ON/OFF command
- AN1 & AN2 are used to give analog inputs (here, reference speed and current data) to controller

Working

- According to the rotor position information from hall sensor, controller will generate PWM signal to control the inverter
- Inverter output is given to motor & motor operates according to the voltage from inverter