SEEX1016	ELECTRIC DRIVES AND CONTROL (Common to EEE and E&C)	L	T	P	Credits	Total Marks
		3	0	0	3	100

UNIT I CHARACTERISTICS OF ELECTRIC DRIVES 10 hrs.

Electric drives – Advantages – Classes of duty. Speed – Torque Characteristics of various types of loads and drive motors – selection of power rating for drive motors with regard to thermal. Overloading and load variation factors – load equalization – Starting, braking and reversing operations.

UNIT II DC DRIVE 10 hrs.

Speed control of DC motors – Ward Leonard scheme – Drawbacks – Thyristor converter fed DC Drives: single and four quadrant operations. Chopper fed DC Drives: Time ratio control and current limit control – single, two and four quadrant operation.

UNIT III THREE PHASE INDUCTION MOTOR DRIVES 12 hrs.

Speed control of three phase induction motors: Stator control – Stator voltage and frequency control – AC Chopper and Cycloconverter fed induction motor drives. Rotor control – Rotor resistance control and slip power recovery schemes – Static control of rotor resistance using DC Chopper – Static and Scherbius drives – Introduction to vector control based drives, Direct and Indirect Vector Control.

UNIT IV THREE PHASE SYNCHRONOUS MOTOR DRIVES 10 hrs.

Speed control of three phase synchronous motors – Voltage source and current source converter fed synhchronous motors – Commutatorless DC motor- Cycloconverter fed synchronous motors – Effects of harmonics on the performance of AC motors – Closed loop control of drive motors, Marginal angle control and power factor control.

UNIT V DIGITAL CONTROL AND DRIVE APPLICATIONS 8 hrs.

Digital techniques in speed control – Advantages and limitations – DSP based control of drives – Selection of drives and control schemes for steel rolling mills. Paper mills, lifts and cranes.

TEXT BOOKS:

1. Gopal K. Dubey, " Power Semiconductor Controlled Drives", Prentice Hall, 1989.
2. Gopal K. Dubey, "Fundamentals of Electrical Drives", Alpha Science International Ltd, 2001.

REFERENCE BOOKS:

1. Vedam Subramanyam, "Thyristor control of Electric Drives", Tata Mc Graw Hill, New Delhi 1991.
2. S.K.Pillai, " A First Course on Electrical Drives", New age international Publishers Pvt Ltd,1989,Reprint 2004.
3. P.C.Sen, "Thyristor DC Drives", John Wiley & Sons New York 1981.
4. B.K.Bose, "Power Electronic & AC drives", Prentice Hall, 2006.

UNIVERSITY EXAM QUESTION PAPER PATTERN

Max. Marks : 80 Exam Duration : 3 Hrs

PART A : 2 Questions from each unit, each carrying 2 marks 20 marks

PART B : 2 Questions from each unit with internal choice, each carrying 12 marks 60 marks

UNIT I CHARACTERISTICS OF ELECTRIC DRIVE

Speed - Torque characteristics of various types of loads and drive motors - selection of power rating for drive motors with regard to thermal, overloading and load variation factors - load equalizat - starting, braking and reversing operations.

ELECTRICAL DRIVES :

Most of the production equipment used in modern industrial undertakings consists of three important components viz the prime mover, the energy transmitting device and the actual equipment that performs the desired job.

The aggregate of electric motor, the energy transmitting shaft and the control equipment by which the motor characteristics are adjusted and their operating conditions with respect to mechanical load varied to suit particular requirement is called an 'Electrical drive'. The drive together with the load constitutes the drive system.

Industrial loads require operation at any one of a wide range of speeds. These loads are driven by hydraulic, pneumatic or electric motors. The drive has some special features when driven by electric motors. They are :

(i) The speed - torque characteristic of the motor can be very easily modified to suit the load characte

(ii) It has a sufficient overload capacity and can be overloaded for short interval without affecting the life of the motor.

(iii) The motors can be brought to operation without any warming up period.

(iv) An electric motor can operate in all the four quadrants of V-I plane, corresponding to the mechanical quantities, speed and torque.

(v) Another feature of drives employing electric motors is smooth speed control over a wide range.

(vi) Electric motors have good starting torque and can started on load.

(vii) The precise speed required by industrial drives can be easily accomplished by means of an electric mo

(viii) Easy to maintain an electric drive.

(ix) Adaptability to almost any type of environmental operating conditions such as natural forced ventilation totally enclosed, submerged in liquids, exposed to explosive or radioactive environment etc.

(X) No hazardous fuel is required. No exhaust gases are emitted to pollute the environment. The noise level is also low.

(XI) Electric motors are available in a variety of design ratings to make them compatible to any type of load

Classification of Electric Drives :

Electric drives are normally classified into three groups based on their development namely group individual and multimotor electric drives.

Group Drive : If several groups of mechanisms or machines are organised on one shaft and driven or actuated by one motor, the system is called a 'Group Drive' or 'shaft drive'.

The various mechanisms connected may have different speeds. Hence the shaft is equipped with multistepped pulley and belts for connection to individual loads. In this type of drive a single machine whose rating is smaller than the sum and total of all connected loads may be used, because all loads may not appear at the same time. Though this mechanism is ecomical, it is seldom in use because of the following disadvantages.

(i) The efficiency of the drive is low, because of the losses occuring in several transmitting mechanisms.

(ii) The complete drive system requires shut down the motor requires servicing or repair.

(iii) The location of the mechanical equipment being driven depends in the shaft and there is little flexibility in its arrangement.

(iv) The system is not very safe to operate.

(v) The noise level at the work spot is high.

Individual Drive :

In this drive an electric motor is used for transmitting motion to various parts or mechanisms belonging to a single equipment. For example, such a drive in a lathe rotates the spindle, moves and feed and also with the help of gears imparts motion to the lubricating and cooling pumps of the lathe. The main draw back is power loss during transmis to the different parts by means of mechanical parts like gears, pulleys etc. This demerit can be overcome by multimotor drivers.

Multimotor Drives :

In this drive, separate motors are provided for actuatting different parts of the driven mechanism. For example, in travelling cranes, there are three motors. One for hoisting, another for long travel motion and the third for cross travel motion. Multimotor drives have enabled introduction of automation in production process and considerabl increased the productivity of different industrial undertakings. Eg. paper making m/c, rolling mills, metal cutting

Basic Elements of an Electric Drive :

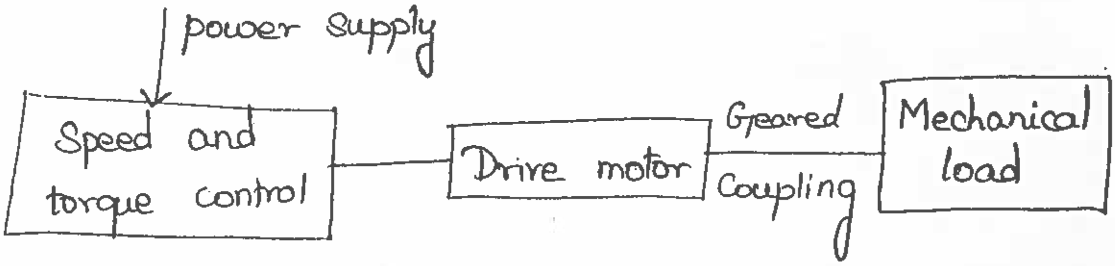


fig. Elements of an electric drive

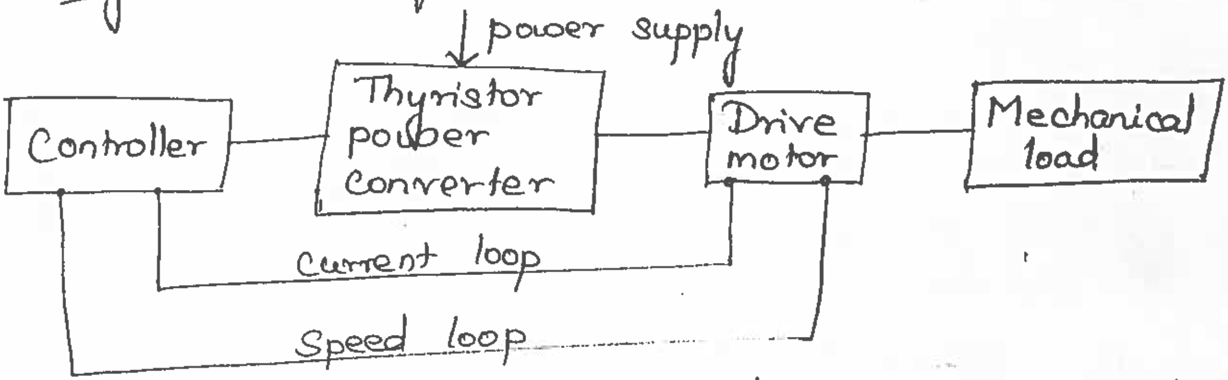


fig. Elements of an electric drive using a static thyristor power converter.

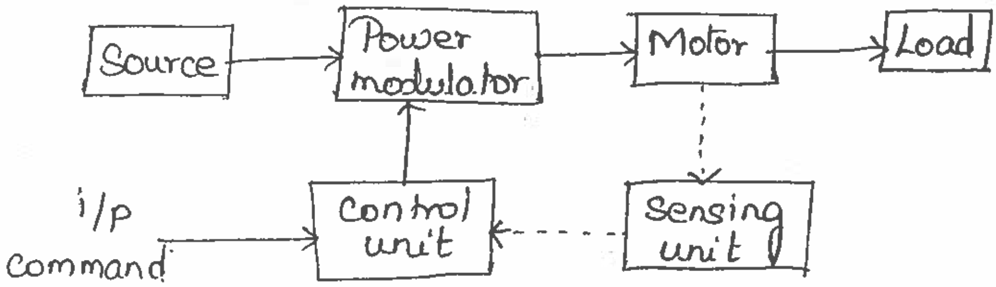


fig. General Electric drive system.

Components of Electric Drives.

1. **Electrical motors and mechanical load:**

DC motor :- shunt motor, series motor, compound
PMDC motor.

AC motor :- (i) Induction motor → Squirrel cage IM
wound rotor IM, linear IM.

(ii) Synchronous motor → wound field
permanent magnet.

* Brushless DC motor, stepper motor and SRM can also be used.

2. **Power Modulators:**

(a) Converters

(i) AC to DC converter
(ii) AC Regulator
(iii) chopper or dc - dc converters
(iv) Inverters
(v) Cycloconverters

(b) Variable Impedance

Variable resistors are commonly used for the control of low cost dc and ac drives and are also needed for Braking of drives.

(c) Switching Circuits:

We need switching ckts to achieve the following operations.

(i) For changing its quadrant operation.

(ii) For operating motors in predetermined sequence.

(iii) To provide inter locking to prevent malfunction.

(iv) To disconnect motor when abnormal operation condition occurs.

3. Source :

Very low power drives are generally fed from single phase source. Low and medium power motors are fed from 400V supply. For higher rating, motors may be rated at 3.3 kV, 6.6 kV, 11 KV. Some drives are powered from a battery. Battery voltage may have 24V, 48V and 110V DC.

4. Control Unit :

When semiconductor converters are used, the control unit will consist of firing circuits, which employs linear and digital integrated circuits and μP, μC, DSP when sophisticated control is required.

5. Sensing Unit : It performs two functions

(i) Speed sensing : It is required for implementation of closed loop control schemes. Speed is usually sensed by using tachometer, digital tachometers, optical encoder, etc.

(ii) Current sensing : It employs two methods.

(a) Use of current sensor (Hall effect sensor)

(b) Non - Inductive resistance shunt in conjunction with an isolation amplifier which has an arrangement for an amplification and isolation b/w power and control ckt

Comparison of DC & AC drives

	DC drives	AC drives
1.	It is bulky, costly, heavy due to commutators	Inexpensive - particular squirrel cage IM
2.	Converters are simple and inexpensive. Converter technology is well established.	Converter is complex, still being developed.
3.	Line commutation of converter is used.	Forced commutation is u
4.	Poor power factor, Harmonic distortion of the current.	For regenerative drives is poor. For non-regenera pf is better.
5.	Fast response, wide range of speed control	Response depends upon the type of control. With the h of solid state converters the speed range is wide.
6.	Small power/weight ratio	Large power/weight ratio
7.	Sparking takes place, so not suitable for explosive environment.	Sparking does not occur. It is suitable for all environment.

Types of Loads

Loads can be of two types - those which provide active load torques and those which provide passive torques.

Active load torques :

Load torques which have the potential to drive the motor under equilibrium conditions are called active load torques. Such load torques usually retain their sign when the direction of the drive rotation is changed. Example - Torque due to the force of gravity and torques due to tension, Compression and torsion undergone by an elastic body.

Consider an electric train, when the train climbs up, the active torque due to gravity opposes the motion. Therefore the driving motor has to generate extra torque to overcome torque due to gravity. The motor produces braking torque to limit the speed within the safe values. This prescribes the features of the active load torque.

Passive load torques :

Load torques which always oppose the motion and change their sign on the reversal of motion are called passive load torques. Eg. Torques due to friction, Cutting.

Classification of loads :

Based on the duty they have to perform the loads are classified as,

1. Continuous constant loads: These loads occur for a long time under the same conditions.

   Eg. Paper making machines, fan type loads.

2. <u>Continuous variable type loads</u> : The load is vari over a period of time but occurs repetitively for longer duration.

Eg. Metal cutting lathes, conveyors, hoisting winches

3. <u>Pulsating loads</u> : Certain types of loads exhibit a torque behaviour which can be thought of as a constant torque superimposed by pulsation.

Eg. Reciprocating pumps and compressors, frame saws, textile looms and generally all machines havin crank shaft.

4. <u>Impact loads</u> : Peak load occurs at regular inter of time. The motors driving these loads are equipped w flywheels for load equalisation.

Eg. Rolling mills.

5. <u>Short time intermittent loads</u> : The load applied particularly in identical duty cycle, each consisting of a period of application of load and one at rest.

Eg. Hoisting mechanisms, Excavaters, all forms of cranes

6. <u>Short time loads</u> : A constant load appears on the drive for a short time and the system rests for the remaining period.

Eg. Battery charging and house-hold equipments.

Choice or selection factors for Electrical Drives :-

1. **Steady State operation Requirements :-**

Nature of speed - torque characteristics, speed regulation, speed range, Efficiency, Duty cycle, Quadrants of operation, speed fluctuations.

2. **Transient operation requirements :-**

Value of acceleration and deacceleration, startin Braking and Reversing performance.

3. **Requirements related to the source :-**

Type of source, magnitude of voltage, voltage fluctuation, power factor, Harmonics.

4. **Other factors :-**

Capital and running cost, maintenance needs, life, space and weight restriction, environment and location, Reliability.

Speed - Torque characteristics of mechanical loads.

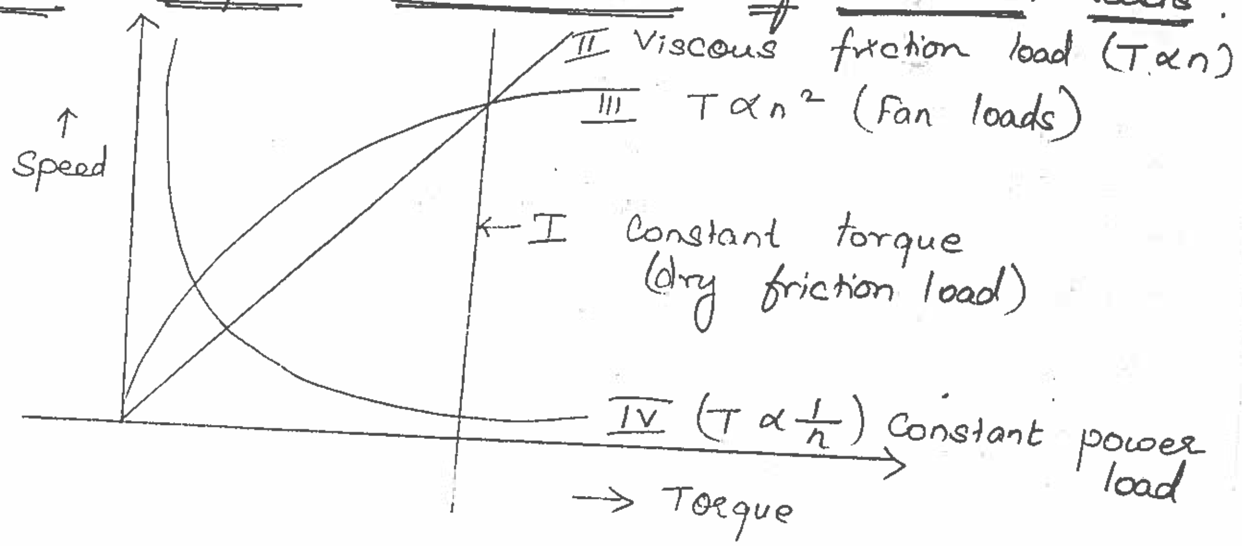


Fig (a) : Speed - torque characteristics of mechanical load.

Mechanical loads exhibit wide variations of speed - torque characteristics. Load torques are generally speed dependent and can be represen by an emperical formula such as

$$T = C\, T_r \left(\frac{n}{n_r}\right)^k \quad \text{---} \quad (1)$$

where : C - proportionality constant

T_r - load torque at rated speed n_r

n - the operating speed.

k - an exponential co-efficient representing the torque dependency on speed.

Fig shows the typical characteristics of various mechanical loads.

Load characteristics are grouped into the following t

1. Torque independent of speed :- (Curve I)

The characteristics of this type of mechanical load are represented by equation (1) when $k=0$ and $c=1$ while the torque is independent of speed, the power the load consumes is linearly dependent on speed ($P = T\omega$). The examples of this type of load are hoists, pumping of water or gas against constant pressure. Shaping, Boring, Drill

2. Torque linearly dependent on speed :- Fan Curve II

The torque is proportional to speed when $k=1$ power is proportional to the square of the speed. This is an uncommon type of load characteristic and usually observed in a complex form of load.

Example : Motor driving a dc generator connected to a fixed resistive load and the field of genera is constant, calendering machines.

3. Torque proportional to the square of the speed ($T \propto n^2$ Curve III)

The torque - speed characteristic is parabolic, $k = 2$. Examples of this type of loads are fans, centrifugal pumps and propellors. The load power requirement is proportional to ω^3 and may be excessive at high speeds.

4. Torque inversely proportional to speed :- ($T \propto \frac{1}{n}$ Curve IV)

In this case $k = -1$. This load usually requi a large torque at starting and at low speed the power consumption of such a load is independent of speeds. Example of this type of load includes milling and boring machines.

Some loads have a combination of the characteristics listed. For example friction torque is inversely proportional to speed at low speeds and a high speeds, it is almost linearly proportional to the speed due to viscous friction.

Speed - Torque characteristics of Electric motors

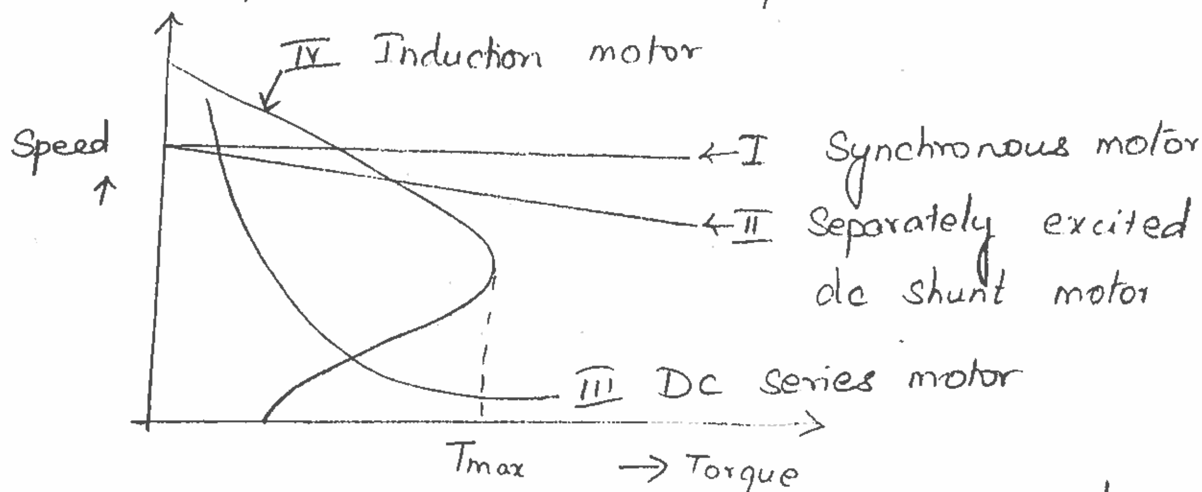


Fig (a). Speed - torque characteristics of conventional moto[rs]

Synchronous or reluctance motors exhibit a constant speed characteristics shown by curve I. At steady state these motors operate at constant speed regardless of the value of the load torque.

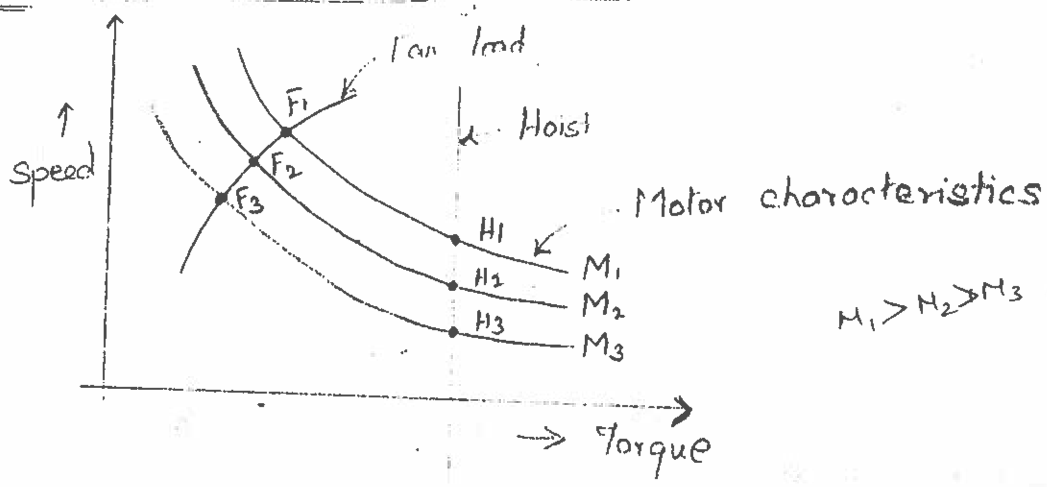
Curve II shows a dc shunt or separately excited motor, where the speed is slightly reduced when the load torque increases.

Curve III shows the torque - speed characteristic of dc motor where $n \propto \frac{1}{T^2}$

In case of Induction motor speed increases linearly with torque, till torque attains maximum value and thereafter speed decreases rapidly as indicated by curve IV in figure(a).

In electric drive applications, electric motors should be selected to match the intended performance of the loads.

Joint speed - torque characteristics of Electrical motors and mechanical loads.



When an electric motor is connected to a mechanical load, the system operates at a speed - torque status that matches the characteristics of an electric motor (M_1, M_2 and M_3). The characteristics are obtained by adjusting the voltage across the terminals of the motor where m, requires higher voltage compare M_2 or M_3. When the motor is driving an elevator, the load torque of a hoist is Independent of speed. For the motor with characteristics M_1, the system operating point is H_1. The co-ordinates of point H_1 determine the speed and torque of the system of the motor such that is exhibits the voltage is reduced such that the new system operating characteristics M_2, the new system operating condition is H_2 and so on.

If the same motor is loaded by a fan and the fan characteristic is as shown in fig. The operating points of the system with the fan are F_1, F_2 & F_3 depending on the motor voltage. Hence speed of the system is not determined by the motor only, but is also heavily dependent on the load characteristics.

Four Quadrant Electric Drive System :

The following conventions govern the power flow analysis of electric drive systems.

1. When the motor torque is in the same direction as the system speed, the machine consumes power from the source and delivers mechanical power to the load. The electric machine operates as a motor.

2. If the speed and torque of the machine are in opposite directions, the machine consumes mechanical power from load and delivers electric power to the source.

Fig. shows the four quadrants of speed - torque characteristics that covers all possible combination of any electric drive system.

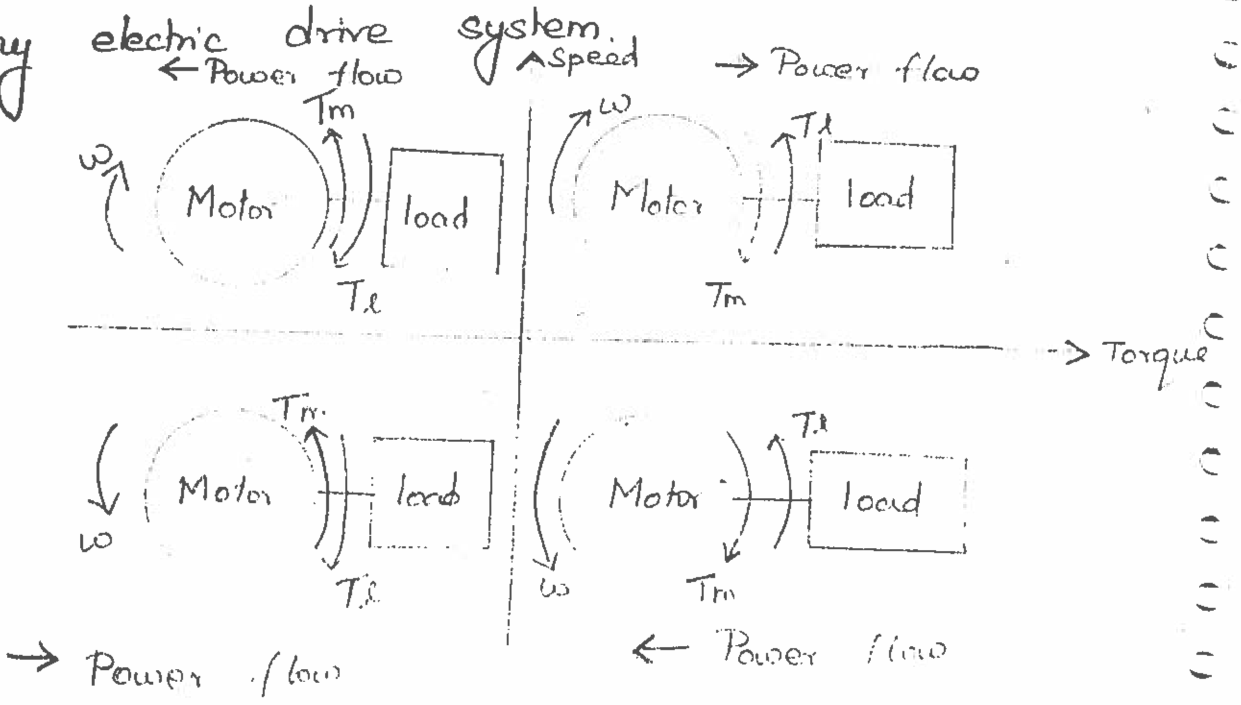


Fig. Four Quadrant Drives

In the first quadrant, the torque of the machine is in the same direction as the speed. The load torque is opposite to the machine torque. The electric machine in this case is operating as a motor. The power flao is from machine to the mechanical load.

In the second quadrant, the speed direction of the system is unchanged, while the load torque and motor torque are reversed. Since the load torque is in the same direction as the speed, the mechanica load is delivering pawer to the machine. The electric machine in this case acts as a generator.

Compared to the first quadrant, the system spee and torque are reversed in the third quadrant. Since machine torque and speed are in the same-direction, the flow of power is from the machine to the load. The machine is therefore acting as a motor rotating in the reverse direction to the speed of the first quadrant.

Ex. A Bi-directional grinding machine operates in I & III quadrants.

In the fourth quadrant, the torques remain unchanged as compared to the first quadrant, but the speed direction changes. The load torque and the speed are in the same direction. Hence the power flows from the load to the machine. The machine in this case operates as a generator.

Ex: When the elevator is going in the downward direction, the motor speed is reversed, but the torque direction remains unchanged.

STARTING :

The most important processes association with controlled electric drive are : starting, speed control, braking and reversing the direction of rotation.

The excessive voltage drop due to the peak starting current may interfere with the supply in such a way that it cannot be tolerated by other equipment connected to the same power supply network. The starting currents will add to the motor heating by an amount that depends upon their rms values and the frequency of starting. The equipment connected to the driving motor may impose strict constraints upon the type of acceleration cycle and upon the maximum permissible acceleration.

Methods of Starting electric motors :

The various methods of starting of the various electric motors are as follows.

(i) Full voltage starting :

This involves the application of full line voltage to the motor terminals. This is also called as direct on line starting. DC motors upto 2kw and squirrel cage IM and synchronous motors upto 4 or 5 kw are usually line started.

(ii) Reduced voltage Starting :

In order to avoid heavy starting current and the consequent voltage dip in the supply lines, motors are started by applying a reduced voltage ~~to their~~ ~~terminal~~ ~~voltage~~ to their terminals and subsequently increasing it to its normal value.

Reduced voltage starting of IM is achieved by (i) Stator resistance starting (ii) Star - delta starting (iii) Auto - transformer starter. (iv) stator reactor starting. The starting torque is reduced in this case.

(iii) Increased torque Starting :

With a wound rotor IM, resistance can be added in the rotor circuit so as to decrease the starting current while increasing the starting torque, even, upto the value of maximum torque that can be developed by the motor.

(iv) Starting by means of smooth variation of voltage or frequency :

With ac motor - dc generator sets, dc motors can be started by smooth variation of applied voltage and with variable frequency sources, both induction and synchronous motors can be started by smooth variation of supply frequency, simultaneously varying proportionally the applied voltage to the motors.

Methods to reduce the Energy loss during starting

The following methods are used to reduce the loss in energy during starting.

(i) Reducing the moment of inertia of the rotor

The energy loss in motors during transient operation can be reduced by reducing the moment of inertia of the drive system. In order to achieve such reduction, a single motor of certain power rating can be replaced by two motors of one-half of the rating. Another method is to use specially designed motors having large axial length.

(ii) Starting of dc shunt motors by smooth variation of applied voltage:

This method necessitates the presence of a variable dc voltage source. Smooth adjustment of applied voltage is equivalent to applying the voltage in a large number of small voltage steps. The loss in energy during starting with equal steps of voltage can be expressed as

$$W_{st} = m\left[\frac{1}{2} J \left(\frac{\omega_0}{m}\right)^2\right].$$

Larger the steps in voltage, less will be the energy loss during starting.

(IV) Starting of IM by smooth variation of supply frequency:

In this method the speed is varied in a very large number of steps. If the speed steps are equal in magnitude and a large number of steps in frequency are effected, the loss in energy during starting can be reduced.

Braking of Electric Motors:

While operating electrical drives it is often necessary to stop the motor quickly and also reverse it. In applications like cranes or hoists the torque of the drive motor may have to be controlled so that the loads does not have any undesirable acceleration. The speed and accuracy of stopping or reversing operations improve the productivity of the system and quality of the product. In the above applications, braking torque is required, which may be supplied either mechanically or electrically.

Based on the purpose for which braking is employed, there are two form of braking, namely

(i) braking while bringing the drive to rest

(ii) braking while lowering the loads.

In the first type, the device used for braking absorbs the kinetic energy for the moving parts. in the second, it absorbs the potential energy in addition to the ~~potential~~ kinetic energy.

Braking while stopping is employed to reduce the time taken to stop, stopping exactly at specified point, controlling the speed at which the load comes down and limiting it to a safe value - ie to feed power back to the supply

Comparison of Electrical and Mechanical Braking

Mehanical Braking	Electrical Braking
1. Mechanical brakes require frequent maintenance. They are prone to wear & tear.	Very little maintenance. Dust free operation due to absence of mechanical equipment.
2. The energy of the rotating parts is wasted as heat in friction. Heat is generated during braking.	The energy of the rotating parts can be converted to electrical energy which can be utilised or returned to the mains.
3. Braking may not be smooth	Smooth braking without snatching.
4. Brake shoes, brake linings, brake drum are required.	Equipment of higher rating than the motor rating may be required.
5. This braking can be applied to hold the system at any position	Cannot produce holding torque.

Types of Braking :

There are 3 types of electric braking, Viz

(i) Regenerative Braking

(ii) Rheostatic or dynamic Braking

(iii) Plugging or reverse current Braking.

(i) Regenerative Braking :

$E > V$

Regenerative braking implies operating the motor as a generator, while it is still connected to the supply network. Mechanical energy is converted into electrical energy, part of which is returned to the supply. Rest of the energy is lost as heat in the windings and the bearing of the electrical machine.

For regenerative braking to take place ; the source motor circuit should have the ability to carry current in either direction.

(ii) Dynamic braking or rheostatic Braking :

In this method mechanical energy is converted into electrical energy, which is dissipated as heat in the resistance of the machine winding or in resistors connected to them as an electrical load.

(iii) Plugging or reverse current braking :-

Plugging involves reconnecting the power supply to the motor so that it tends to drive the opposite direction. This is the most inefficient technique.

Note : Regenerative braking cannot be employed DC series motors because for the regenerative braking to take place, the motor induced emf (Back emf) must exceed the supply voltage and the armature current should reverse. The reversal of armature current in series motor will reverse the current through the field, therefore the induced emf will also reverse setting up a short circuit condition. Moreover the speed is extremely high even before the motor reaches actual no-load

Selection of motor power rating :

(a) Requirements :-

* The power rating of a motor for a specified application must be carefully chosen to achieve economy with Reliability.

* Insufficient rating fails to drive the load
* Liberal power rating leads to extra initial cost and losses.

1. Motor selected should be capable of driving the load satisfactorily.

2. Selection of a p... " by its speed torque" characteristics which influenced the speed - torque characteristics would match the speed - torque characteristics of the load.

3. If the power rating is decided liberally, the extra initial cost & extra loss of energy due to operation below rated power makes the choice uneconomi

4. Induction and synchronous motor operates at a lower power factor when operating below the rated power.

Thermal model of motor for heating and cooling :-

A simple thermal model of a m/c can be obtained be assuming machine to be a homogeneous body. Although inaccurate, such a model is good enough to select the motor rating for a given application.

let,

P_1 → Heat developed, joules/sec (or) watts

P_2 → Heat dissipated to cooling medium, watts.

W → weight of the active parts of machine, kg.

h → Specific heat, Joules/kg

A → Cooling surface, m^2

d → co-efficient of heat transfer. joules/sec/m^2/°c.

θ → mean temp rise, °c.

During a time increment dt, let the m/c temp rise be $d\theta$. since,

$$\left.\begin{matrix}\text{Heat absorbed in} \\ \text{the m/c}\end{matrix}\right\} = \text{Heat dissipated inside the m/c} - \left.\begin{matrix}\text{Heat dissipated the} \\ \text{surrounding} \\ \text{Cooling medium}\end{matrix}\right\}$$

$$Wh\,d\theta = P_1\,dt - P_2\,dt \quad \text{---} (1)$$

$$\text{Since } P_2 = \theta\, dA \quad \text{---} (2)$$

Sub eqn (2) in (1)

$$Wh\,d\theta = P_1\,dt - \theta dA\,dt$$

$$Wh\,d\theta = [P_1 - \theta dA]\,dt$$

$$Wh\,\frac{d\theta}{dt} = P_1 - \theta\,dA$$

$$\begin{bmatrix} C = Wh \\ D = dA \end{bmatrix}$$

$$C\,\frac{d\theta}{dt} = P_1 - D\theta \rightarrow (3)$$

$$\begin{bmatrix} \theta_{ss} = \frac{P_1}{D} \\ \tau = \frac{C}{D} \end{bmatrix}$$

where,

$C \rightarrow$ Thermal capacity of m/c, W/°c

$D \rightarrow$ heat dissipation constant, W/°c.

$$C\frac{d\theta}{dt} + D\theta = P_1$$

$\div D$

$$\frac{C}{D}\,\frac{d\theta}{dt} + \theta = \frac{P_1}{D}$$

$$\tau\,\frac{d\theta}{dt} + \theta = \theta_{ss}$$

$$\tau\,\frac{d\theta}{dt} + \theta = 0$$

$$(\tau D + 1)\,\theta = 0$$

$$\tau m + 1 = 0$$

$$m = -1/\tau$$

Sol: $y = Ke^{mx} = Ke^{\tau} = ke$

General solution: $y = C.F + P.I$

$$\theta = Ke^{-t/\tau} + \theta_{ss} \longrightarrow (4)$$

K is obtained by substituting $t = 0$

$$\theta = \theta_{ss} + K$$

$$\boxed{K = \theta_1 - \theta_{ss}}$$

θ_1 = Initial temp rise is θ_1

Now, $\theta = \theta_{ss} + [\theta_1 - \theta_{ss}]\, e^{-t/\tau}$

$$\theta = \theta_{ss} + \theta_1 e^{-t/\tau} - \theta_{ss}\, e^{-t/\tau}$$

$$\theta = \theta_{ss}\left[1 - e^{-t/\tau}\right] + \theta_1 e^{-t/\tau} \longrightarrow (5)$$

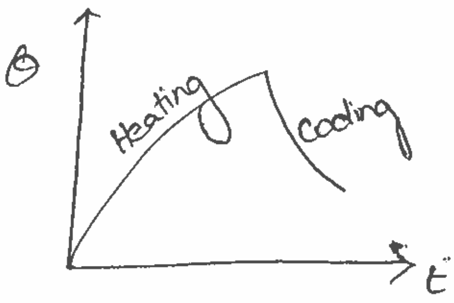
Eqn (5) is the solution of 1st order diff eqn (3).

when temp rise to θ_2. Heat loss will reduce to small value P_1' and cooling begins.

$$C' \frac{d\theta}{dt} = P_1' - D'\theta \longrightarrow (6)$$

take $\theta_{ss}' = \dfrac{P_1'}{D'}$, $\tau' = C'/D'$

$$\theta = \theta_{ss}'\left[1 - e^{-t/\tau'}\right] + \theta_2\, e^{-t/\tau'}$$



A motor operates on a periodic duty cycle in which it is clutched to its load for 10 min and declutched to run on no-load for 20 min. Minimum temp rise is 40°C. Heating and cooling time constants are equal and have a value of 60 min. When load is declutched continuously the temp rise is 15°C.

<u>Determine</u> * Maximum temp during the duty cycle

* Temp when the load is clutched continuou

Given: $t_{on} = 10$ min, $t' = 20$ min, $\theta_1 = 40°c$, $\theta_{ss}' = 1$

τ & $\tau' = 60$ min.

$$\theta_2 = \theta_{ss}(1 - e^{-t/\tau}) + \theta_1 e^{-t/\tau}$$

$$= \theta_{ss}(1 - e^{-10/60}) + 40\, e^{-10/60}$$

$$= 0.1535\ \theta_{ss} + 33.859 \longrightarrow (1)$$

$$\theta_1 = \theta_{ss}'(1 - e^{-t/\tau'}) + \theta_2 e^{-t/\tau'}$$

$$40 = 15(1 - e^{-20/60}) + \theta_2 e^{-20/60}$$

$$\theta_2 = 49.9°c \longrightarrow (2)$$

Sub (2) in (1)

$$\therefore \theta_{ss} = 104.5°c.$$

Determination of motor rating :-

* Continuous duty
* Fluctuating loads.
* Short - time & intermittent duty

Continuous duty :

$$T_{eq} = \sqrt{\frac{T_1^2 t_1 + T_2^2 t_2 + \dots + T_n^2 t_n}{t_1 + t_2 + \dots + t_n}}$$

T_{eq} - equivalent torque

T_1, T_2, T_3 - inst. torques

Motor power rating $\Rightarrow$ $\boxed{P_r = \frac{T_{eq} N}{975}}$

The equivalent power is

$$P_{eq} = \sqrt{\frac{P_1^2 t_1 + P_2^2 t_2 + \dots + P_n^2 t_n}{t_1 + t_2 + \dots + t_n}}$$

Short - time duty

$$P_m = \frac{1}{\sqrt{1 - e^{-t_{on}/\tau}}}$$

$$P_m = \sqrt{P_h}.$$

$$P_h = \frac{1}{1 - e^{-t_{on}/\tau}}$$

Intermittent duty load :

$$P_m = \sqrt{\frac{1 - e^{-t_{on}/\tau - t_{off}/\tau}}{1 - e^{-t_{on}/\tau}}}$$

* Determine the half an hour rating of a 20 kW motor having a time constant of 2 hour. Assume that the motor cools down completely between each load period.

The full load rating of motor = 20 kW

The rating of the motor for short time duty } $P = \sqrt{P_h} \times 20$

$$= \frac{20}{\sqrt{1 - e^{-t_{on}/\tau}}} = \frac{20}{\sqrt{1 - e^{-30/120}}}$$

$$= 42.45 \text{ kW}$$

* Find the rating of a 120 kW motor when subjected to a duty cycle of 20 min on full load followed by 40 min on no load. The heating and cooling time constant of motor are 100 and 120 min respectively. Assume that the losses are proportional to square of load current.

Here,

$t_{on} = 20$ min

$t_{off} = 40$ min

$\tau = 100$ min

$\tau' = 120$ min

$$P_m = \sqrt{P_h} = \sqrt{\frac{1 - e^{-t_{on}/\tau - t_{of}/\tau'}}{1 - e^{-t_{on}/\tau}}}$$

$$= \sqrt{\frac{1 - e^{-\frac{20}{100} - \frac{40}{120}}}{1 - 0.818}}$$

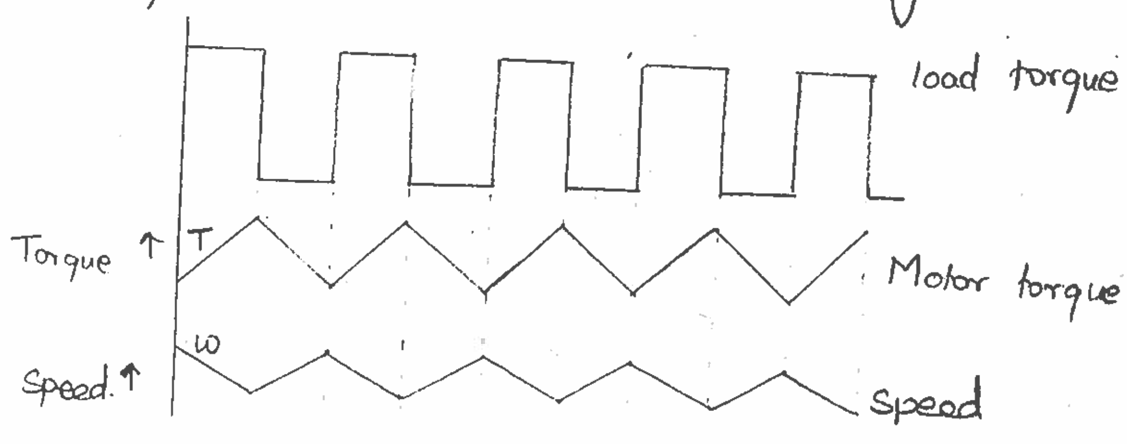
$$= 1.5$$

∴ The rating of the motor is $120 \times 1.5 = 180$ kW

Load Equalisation :-

In some drive applications, load torque fluctuate widely within short intervals of time. For example, in pressing machines a large torque of short duration is required during pressing operation, otherwise the torque is nearly zero. Because of fluctuating load, the motor draw a very heavy current during high load condition which may cause a large voltage drop of the line. This may affect other consumers who will experience voltage fluctuations. Also the motor experiences a shock during each cycle of load variation. Therefore, the equalization of load is achieved by means of a flywheel connected to the load shaft. When heavy load is applied, the motor speed decrease and flywheel will supply K.E. to the motor. During light load condition, the motor speed ↑es and the flywheel stores the energy. Thus the load on the motor is equalized.

If the motor speed ↓ linearly with ↑ in torque, then the variation of speed, load torque, motor torque with time is shown in graph.



For linear variations, if ω_o is the no load speed and 'T_o' the no load torque and if ω & T are the speed and torque at any instant of time, ω_r & T_r are the rated speed and torque of the motor,

the following relations are true ;

$$\omega - \omega_o = K(T - T_o) \longrightarrow (1)$$

$$\omega_r - \omega_o = K(T_r - T_o) \longrightarrow (2)$$

dividing eqn (1) & (2)

$$\frac{\omega - \omega_o}{\omega_r - \omega_o} = \frac{k(T - T_o)}{K(T_r - T_o)}$$

$$\therefore \omega - \omega_o = \frac{T - T_o}{T_r - T_o}(\omega_r - \omega_o) \longrightarrow (3)$$

Since $T_o = 0$

$$\omega - \omega_o = \frac{T}{T_r}(\omega_r - \omega_o)$$

$$\omega = \omega_o + \frac{(\omega_r - \omega_o)}{T_r} \cdot T \longrightarrow (4)$$

$$\frac{d\omega}{dt} = \frac{\omega_r - \omega_o}{T_r} \cdot \frac{dT}{dt}$$

$$\cancel{-J\frac{\omega_r - \omega_o}{T_r}\frac{dT}{dt} + T = T_l}$$

$$\cancel{J\frac{\omega_o - \omega_r}{T_r}\frac{dT}{dt} + T = T_l}$$

If T_l is load torque, the general equation of motor is,

$$T - T_l = J \frac{d\omega}{dt} \rightarrow (5)$$

$$T - T_l = J \frac{\omega_r - \omega_0}{T_r} \cdot \frac{dT}{dt}$$

$$-J \frac{\omega_r - \omega_0}{T_r} \frac{dT}{dt} + T = T_l$$

$$J \frac{\omega_0 - \omega_r}{T_r} \frac{dT}{dt} + T = T_l \quad \text{———} \quad (6)$$

If, $J \dfrac{\omega_0 - \omega_r}{T_r} = \tau_m \longrightarrow (A)$

Then, $\tau_m \dfrac{dT}{dt} + T = T_l \longrightarrow (7)$

Solution is,

$$T = T_l \left(1 - e^{-t/\tau_m}\right) + T' e^{-t/\tau_m} \longrightarrow (8)$$

where T' is the torque developed by the motor at the instant when the heavy load is applied or removed.

$T_{lh} \rightarrow$ heavy load for a period t_h. The motor torque fluctuates between T_{min} & T_{max} then eqn (8) becomes

$$T_{max} = T_{lh} \left(1 - e^{-t_h/\tau_m}\right) + T_{min}\, e^{-t_h/\tau_m} \quad \text{———} \quad (9)$$

|||ly $T_{ll} \rightarrow$ light load for a period t_l.

$$T_{min} = T_{ll} \left(1 - e^{-t_l/\tau_m}\right) + T_{max}\, e^{-t_l/\tau_m} \rightarrow (10)$$

Now from eqn (9)

$$T_{max} = T_{lh} - T_{lh}\, e^{-t_h/\tau_m} + T_{min}\, e^{-t_h/\tau_m}$$

$$= T_{lh} - \left[T_{lh} - T_{min}\right] e^{-t_h/\tau_m}$$

$$T_{max} - T_{eh} = -\left[T_{eh} - T_{min}\right] e^{-t_h/\tau_m}$$

$$\frac{T_{eh} - T_{max}}{T_{eh} - T_{min}} = e^{-t_h/\tau_m} \longrightarrow (11)$$

|||ly eqn (10)

$$T_{min} = T_{el} - T_{el}\, e^{-t_l/\tau_m} + T_{max}\, e^{-t_l/\tau_m}$$

$$T_{min} = T_{el} - (T_{el} - T_{max})\, e^{-t_l/\tau_m}$$

$$T_{min} - T_{el} = -(T_{el} - T_{max})\, e^{-t_l/\tau_m}$$

$$\frac{T_{min} - T_{el}}{T_{max} - T_{el}} = e^{-t_l/\tau_m} \longrightarrow (12)$$

Taking log for eqn (11) & (12)

$$-\frac{t_h}{\tau_m} = \log_e\left[\frac{T_{eh} - T_{max}}{T_{eh} - T_{min}}\right]$$

$$\tau_m = \frac{t_h}{\log_e\left[\frac{T_{eh} - T_{min}}{T_{eh} - T_{max}}\right]} \quad \text{——} \ (13) \ \text{——} \ (B)$$

$$-\frac{t_l}{\tau_m} = \log_e\left[\frac{T_{min} - T_{el}}{T_{max} - T_{el}}\right]$$

$$\tau_m = \frac{t_l}{\log_e\left[\frac{T_{max} - T_{el}}{T_{min} - T_{el}}\right]} \quad \text{——} \ (14) \ \text{——} \ (C)$$

Compare (A) & (B)

$$J = \tau_m \times \frac{T_r}{\omega_0 - \omega_r}$$

$$= \frac{T_r}{\omega_0 - \omega_r}\left[\frac{t_h}{\log_e\left(\frac{T_{eh} - T_{min}}{T_{eh} - T_{max}}\right)}\right] \quad \text{——} \ (15)$$

Compare (A) & (C)

$$J = \frac{T_r}{W_0 - W_r}\left[\frac{t_l}{\log_e\left[\frac{T_{max} - T_{ll}}{T_{min} - T_{ll}}\right]}\right] \quad \text{——} \quad (16)$$

Moment of inertia of the flywheel can be calculated either from eqn (15) & (16)

Problem :

* A motor equipped with a flywheel is to supply a load torque of 1000 N-m for 10 sec followed by a light load period of 200 N-m long enough for the flywheel to regain its steady-state speed.. It is desired to limit the motor torque to 700 N-m. What should be the moment of inertia of flywheel? Motor has an inertia of 10 kg-m². Its no load speed is 500 rpm and the slip at a torque of 500 Nm is 5%. Assume speed-torque characteristics of motor to be a straight line in the region of interest.

Soln :

$T_{lh} = 1000$ N-m, $t_h = 10$ sec, $T_{ll} = 200$ Nm

$T_{max} = 700$ Nm, $T_{min} = 200$ N-m, $S = 0.05\%$

$N_0 = 500$ rpm, $T = 500$ N-m

No load speed W_0 $= \frac{500 \times 2\pi}{60} = 52.36$ rad/sec $= \frac{N_0 2\pi}{60}$

Speed at $T = 500$ N-m is $= (1 - 0.05)\,52.36$ N_0

$= 49.74$ rad/sec

$$J = \frac{17}{\omega_0 - \omega_r}\left[\frac{t_h}{\log_e\left[\frac{T_{eh} - T_{min}}{T_{eh} - T_{max}}\right]}\right]$$

$$= \frac{500}{52.36 - 49.74}\left[\frac{10}{\log_e\left[\frac{1000 - 200}{1000 - 700}\right]}\right]$$

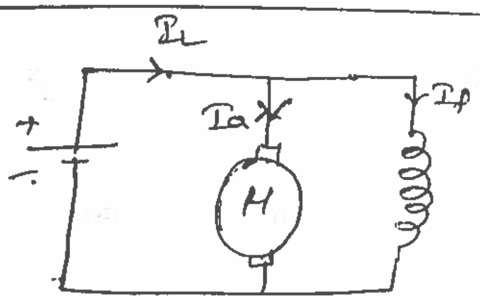
$$= 1871.8 \ kg - m^2$$

Moment of inertia of the flywheel $= 1871.8 - 10$

$= 1861.8 \ kg - m^2$

Speed - Torque Characteristics :

D.C. Shunt Motor $\rightarrow$ Constant flux motor



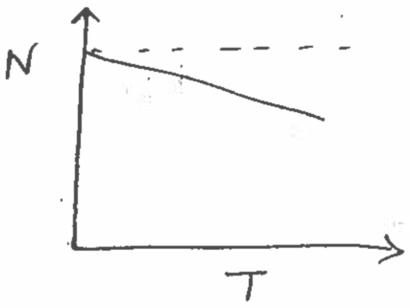
$I_L = I_a + I_{sh}$ (Field wdg is constant

$I_{sh} = V/R_{sh}$

$V = E_b + I_aR_a + V_{brush}$

$\hookrightarrow$ Neglect

$\boxed{\phi \propto I_{sh}}$



As load $\uparrow$, $I_a \uparrow$

I_aR_a drop also $\uparrow$

Hence supply voltage $\downarrow$

$(V - I_aR_a)$ and speed $\downarrow$

$T \propto \phi I_a$ $\quad$ $\phi \rightarrow$ constant

$\therefore T \propto I_a$

DC Series Motor

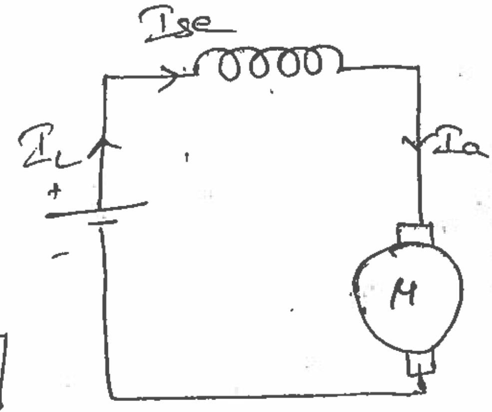
Field wdg is connected in series with armature and supply

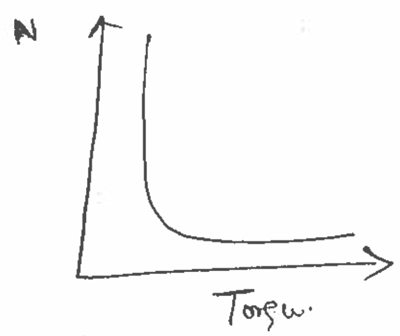
$$I_L = I_{se} = I_a$$

$$V = E_b + I_a(R_a + R_{se}) + V_{brush}$$

$$\phi \propto I_{se} \propto I_a$$

$$\boxed{T_a \propto I_a^2} \qquad N \propto \frac{1}{I_a}$$





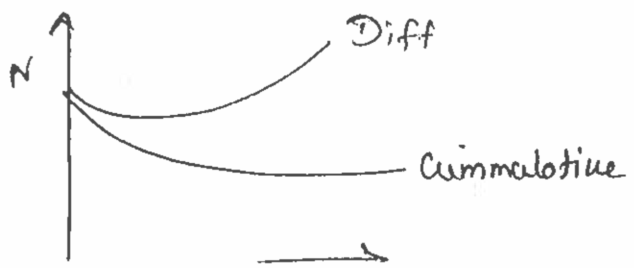
{T ↑ when load ↑
speed ↓}

On no load, torque is very less and hence speed increases to degerously high value.

DC compound motor:

Cumulative
↓
Capable of developing large amount of torque at low speed
↓
||| to series

Differential
↓
[It can run at resonable speed not with dangerously high speed like series]
↓
at light & no load condition.



Induction Motor :

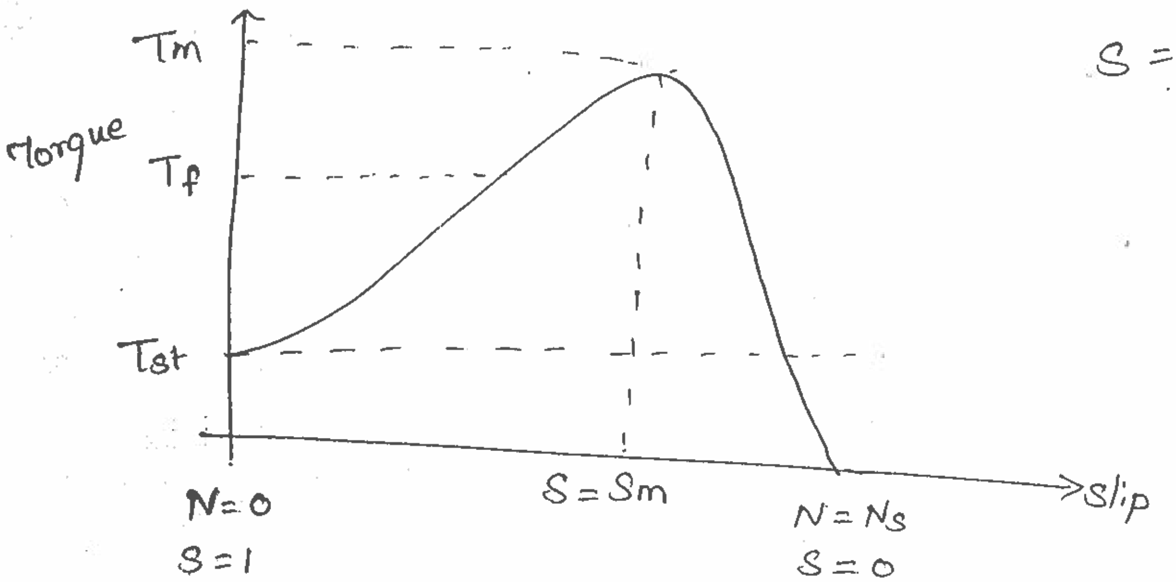
$$T = \frac{K S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

For max torque

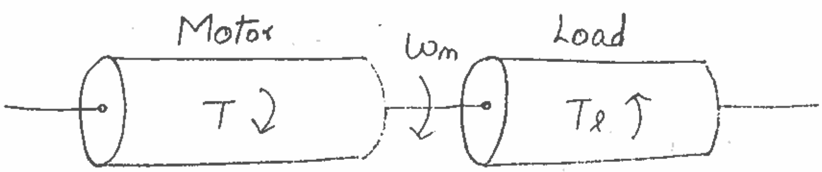
$$\frac{dT}{ds} = 0 \;, \quad S = \frac{R_2}{X_2} \;, \quad S_m = \frac{R_2}{X_2} \Rightarrow T_{max}$$

$$\boxed{T_m = K \frac{E_2^2}{2 X_2}} \; Nm$$

$$S = \frac{N_S - N}{N_S}$$



Fundamental Torque Equation :-



J – polar moment of inertia of motor - load system referred to the motor shaft kg-m^2.

W_m – Instantaneous angular velocity of motor Shaft rad/sec.

T – Instantaneous value of developed motor torque

T_l – Instantaneous value of load torque, referred to motor shaft, N-m.

II - DC Drive

Speed control of DC motor - Ward Leonard scheme Drawbacks - Thyristor converter fed DC drives : Single and four quadrant operation. Chopper fed DC Drives : Time ratio control and current limit control - Single, two and four quadrant operation.

Introduction :

The applied i/p vtg to dc motor is

$$V_a = I_a R_a + E_b$$

$E_b \rightarrow$ back emf

The motor back emf is given by

$$E_b = \frac{\phi Z N P}{60 A} \qquad \because \omega = \frac{2\pi N}{60}$$

$$= \left(\frac{ZP}{60A}\right)\phi N$$

$$= \left(\frac{ZP}{60A}\right)\phi \frac{\cancel{60}\,\omega_m}{2\pi} = \left(\frac{ZP}{\cancel{60}A}\right)\phi\,\omega_m$$

$$\boxed{E_b = K_b \phi \omega_m}$$

Torque developed in the motor $T = \left(\frac{ZP}{2\pi A}\right)\phi I_a$

$$\therefore \boxed{T = K_b \phi I_a}$$

For separately excited, shunt motor ϕ is constant

$$T_d = K_b I_a$$

For series motor $\phi \propto I_a \Rightarrow I_a = I_f$

$$\therefore T_d = K_b I_a^2$$

Problem :

A 500 V shunt motor runs at its speed of 250 r.p.m. when the I_a is 200 A, R_a is 0.12 Ω. Calculate the speed when a resistance is inserted in the field winding, reducing the shunt field to 80% of normal value and I_a is 100 A

Soln :

$$E_{b1} = V - I_{a1} R_a$$
$$= 500 - 200 \times 0.12 = 476\,V$$
$$E_{b2} = V - I_{a2} R_a$$
$$= 500 - 100 \times 0.12 = 488\,V$$

$$\frac{E_{b2}}{E_{b1}} = \frac{N_2}{N_1} \times \frac{\phi_1}{\phi_2}$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_2}{\phi_2} = \frac{488}{476} \times \frac{\cancel{\phi_1}}{0.8\cancel{\phi_1}} \times N_1$$

$$\boxed{\therefore N_2 = 320\ rpm}$$

Problem :

A 230V, 750 rpm 25A dc series motor is driving at rated condition, a load whose torque is proportional to speed squared. The combined resistance of armature and field is 1 Ω. Calculate motor terminal voltage and current for a speed of 400 rpm.

Soln :

$$T \propto \phi I_a \propto I_a^2 = I^2$$

$$\frac{T_1}{T_2} = \frac{I_1^2}{I_2^2} \qquad \phi \propto I_a \propto I$$

$$\frac{T_1}{T_2} = \left(\frac{N_1}{N_2}\right)^2 = \left(\frac{750}{400}\right)^2 = \frac{(25)^2}{I_2^2}$$

$$\therefore I_2 = 13.34\ A$$

$$N \propto \frac{-}{\phi}$$

$$\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2} \times \frac{\phi_1}{\phi_2}$$

$$\frac{V - I_a R_{a1}}{V - I_2 R_{a2}} = \frac{I_1}{I_2} \times \frac{N_1}{N_2}$$

$$\frac{230 - 25 \times 1}{V_2 - 13.34 \times 1} = \frac{25}{13.34} \times \frac{750}{400}$$

$$\boxed{V_2 = 71.65V}$$

Speed Control of DC Motor

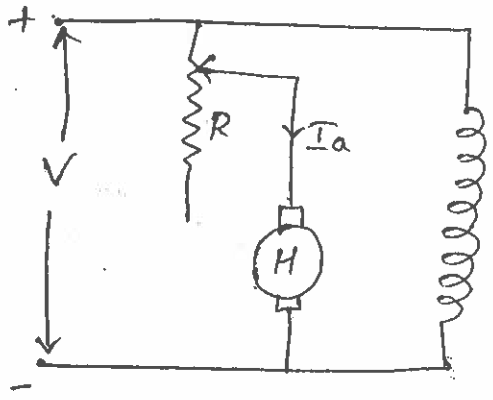
$$N \propto \frac{V - I_a R_a}{\phi} \propto \frac{E_b}{\phi}$$

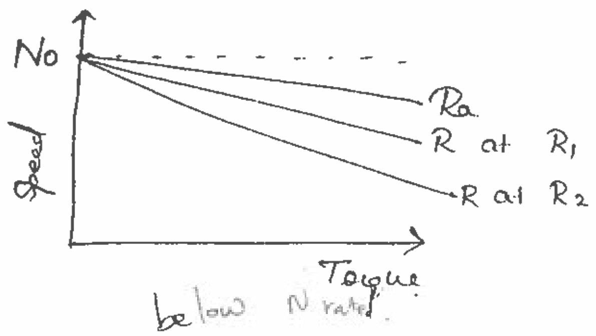
Speed can be controlled by any one of the following methods

1. By varying resistance in the armature ckt
   ↳ Armature Resistance Control
2. By varying the flux
   ↳ Field flux control
3. By varying applied voltage
   ↳ Armature voltage control

SHUNT MOTOR

(i) By varying the resistance in the armature circuit:



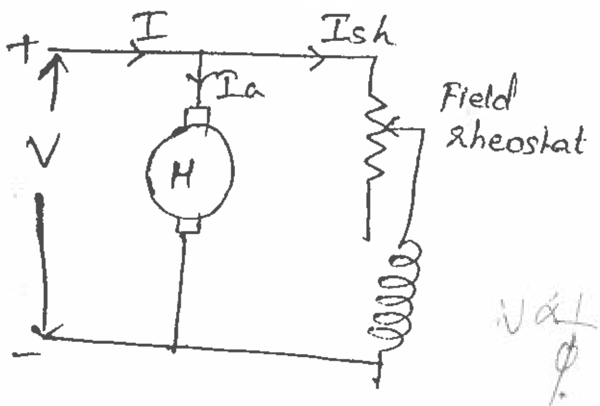


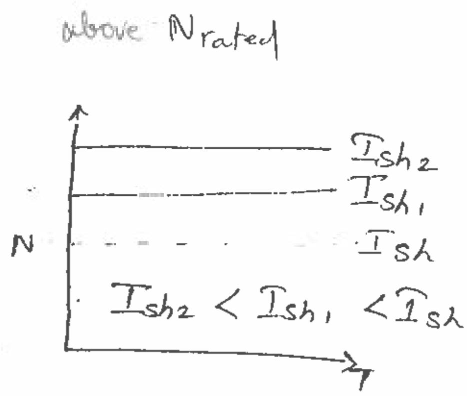
The variable resistance R is connected in series with the armature circuit. The input voltage V is cons. the speed of the motor is controlled by varying the resis. If the resistance is maximum, the potential drop across the armature is decreased.

∴ The motor speed also decreases

$$N = \frac{V - I_a(R_a + R)}{K_b \phi}$$

(ii) Flux Control



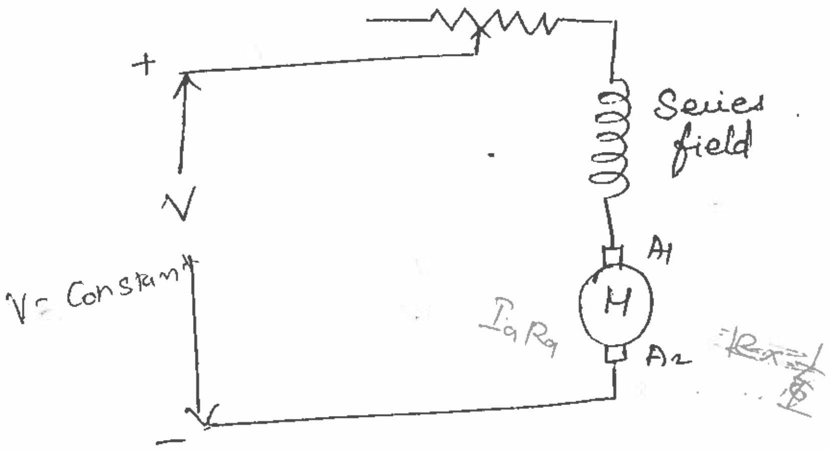


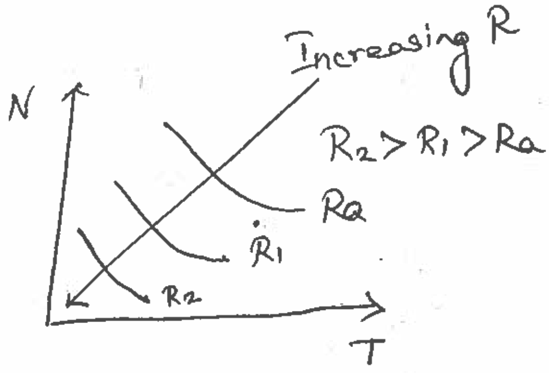
$N \propto \frac{1}{\phi}$

Speed is inversely proportional to flux. By varying the flux, speed can be varied. The flux can be changed by varying the field current I_{sh}. It is obtained by a variable resistance connected in series with the shunt field wdg. By varying the field circuit resistance, the shunt field current can be decreased. Hence the speed is increased by decreasing the flux. This method of speed control can be used for increasing the speed of the motor, above its rated speed.

SERIES MOTOR :

(i) Variable resistance in series with armature :



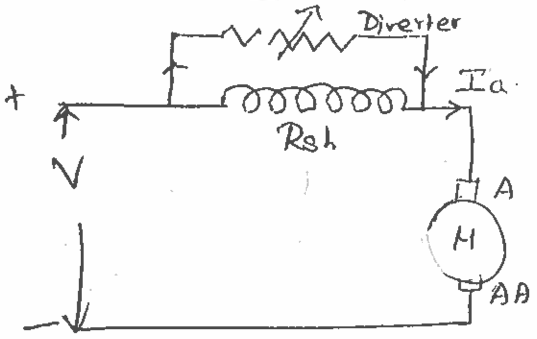


The variable resistance R_1 is connected in series with armature. By increasing the resistance, the ~~armature~~ voltage ~~drop~~ applied across the armature terminal can be decreased. By reducing the voltage across the armature, the motor speed also decreases

$\because N \propto E_b$

(ii) Flux Control :

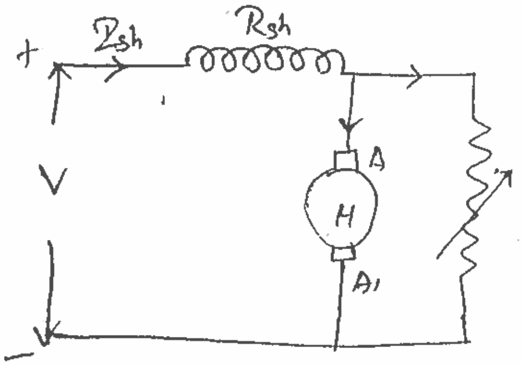
* Field divertor :



A variable resistance is Connected across the series field winding. By varying the resist the current flow through the series field changes. Due to ↓ in I the ϕ can be ↓sed and hence the motor speed ↑es.

$N \propto \frac{1}{\phi}$ ϕ Vary N Vary

* Armature divertor :



A variable resistance is connec across the armature. The dc mo speed can be controlled by the armature diverter. In this method speed can be lowered than the nor speed. For constant torque opera Ia is ↓sed then the ϕ is ↑ed. $T \propto I_a \phi$

Hence current is increased, due to this the series field flux also increases. Then the speed of motor can be decreased $\left(N \propto \frac{1}{\phi}\right)$.

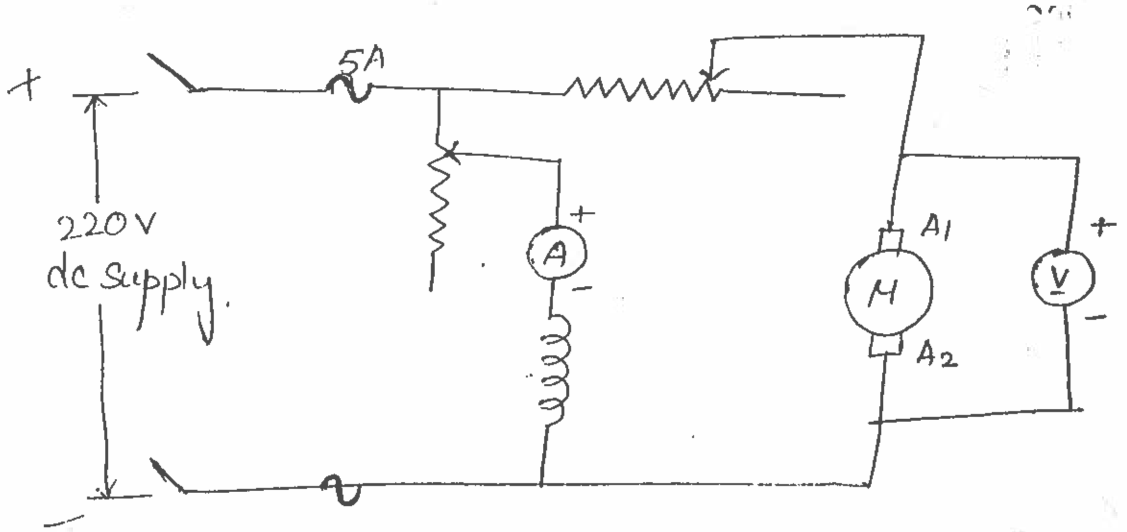
Adv :

(i) Smooth and easy Control
(ii) Speed control above rated speed is possible
(iii) I_f is small, size of rheostat is also small.
(iv) I_f is less, power loss is less.

Dis adv :

(i) Below rated speed is not possible.
(ii) $\phi \downarrow$, $N \uparrow$ very high speed affects the commutation making motor operation unstable.

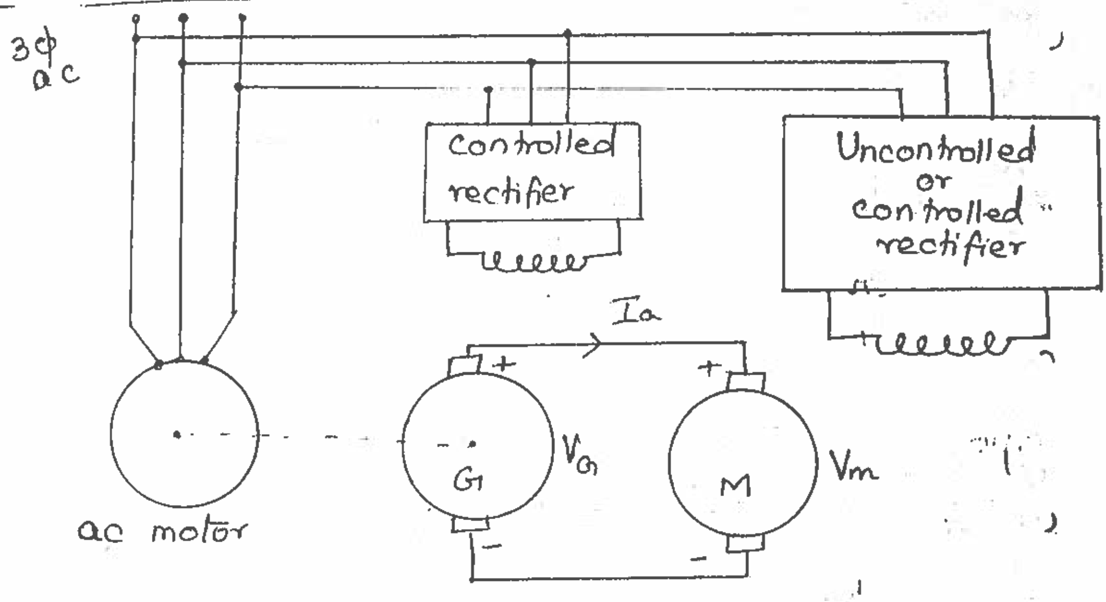
Practical Circuit :



Armature voltage control :- I_f Constant, V_a, N

Flux control method :- V_a Constant, I_f, N

WARD - LEONARD DRIVE :



Ward Leonard control, also known as the Ward Leonard Drive System, was a widely used DC motor speed control system introduced by Hary Ward Leonard in 1890. A ward Leonard drive is a high-power amplifier in the Multi-Kilowatt range, built from rotating electrical machinery. A ward Leonard drive unit consists of a

Motor and generator with shafts coupled together. The motor, which turns at a constant speed, may be AC or DC powered.

The generator is a DC generator, with field & armature windings. The input to the amplifier is applied to the field windings and o/p comes from the armature windings. The amplifier output is connected to a second motor, which moves the load. With this arrangement, small changes in current applied to the i/p result in large changes in o/p, allowing smooth speed control. Armature voltage control only controls the motor speed from zero to motor base speed. If higher motor speeds are needed the motor field current can be lowered.

It consist of a separately excited generator feeding the dc motor to be controlled. The generator is driven at a constant speed by an ac motor connected to 50 Hz ac mains. One of the important feature of this drive is the inherent ability for regenerative braking down to very low motor speeds. This combined with the variation of armature voltage in either direction allows efficient operation of drive in all the four quadrants of speed - torque plane.

For regenerative brakings, the o/p of G is reduced below the induced voltage of M by ↓ the G.

field current. This reverses the current flowing throug the armatures of machines G and M. Now, M le M ~~works as generator & G and M. Now, as generator~~ works as generator and M as motor.

Control of generator field is obtained by rheostats when low ratings are involved. For higher power applications or for closed-loop control the field is supplied by a power amplifier which may consists of a controlled rectifier, chopper or transistor amplifier. When the field is controlled by a power amplifier the min speed obtained is of 0.1 of base speed. Even when I_f is zero, enough voltage is generated to make the motor crawl particularly when the load is light. To prevent crawling and to reduce the motor speed to zero, following 3 methods are employed.

(*) Armature circuit is opened.

(*) A differential field winding on the generator is connected across the armature terminals, this will oppose the flux and prevent built-up of a large circulating current.

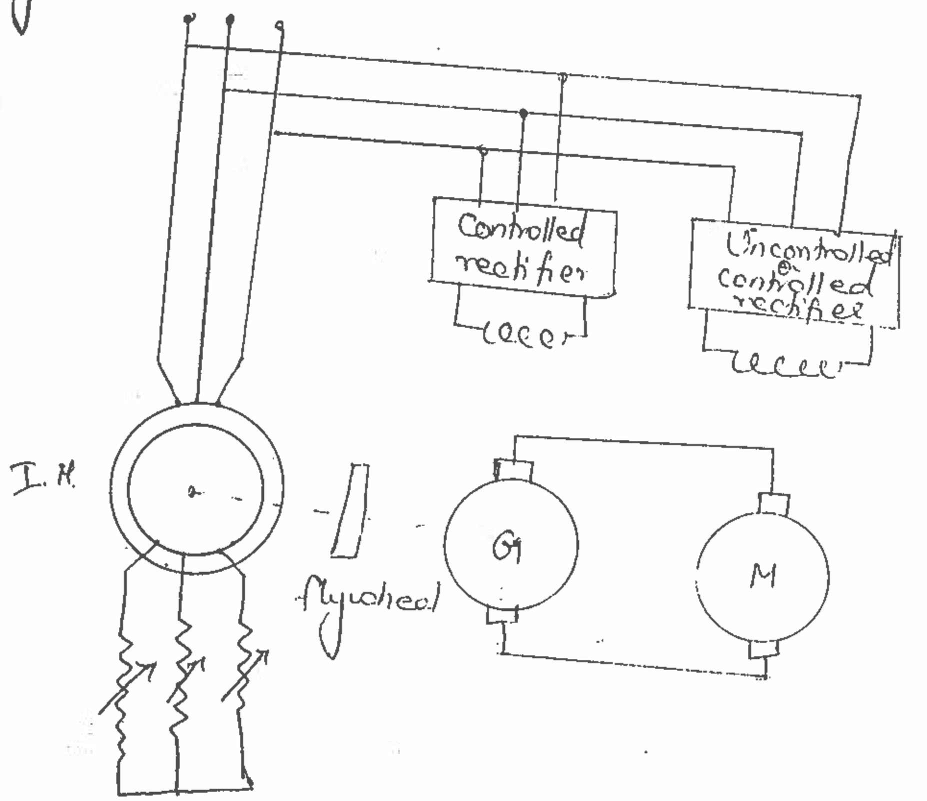
(*) Generator field wdg is connected across the armature terminals such that the current through it produces mmf which opposes the residual mmf. This type of connection is commonly known as

AC motor used here can be inductive or synchronous. IM is cheaper but always operates at lagging PF. Syn → leading PF.

Used in :

→ Rolling Mills
→ Paper mills
→ Elevators
→ M/c tools

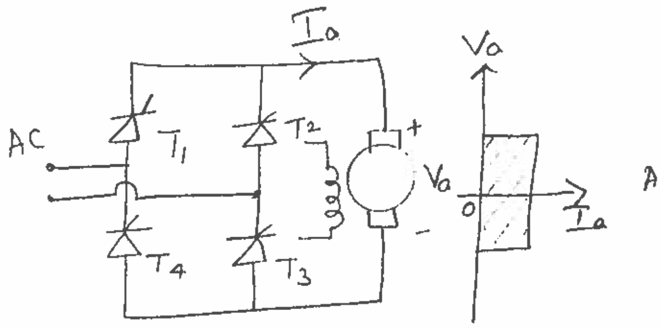
When load is heavy and intermittent, a slip ring IM is employed and a flywheel is mounted on its shaft. This is called the Ward - Leonard Ilgener scheme.



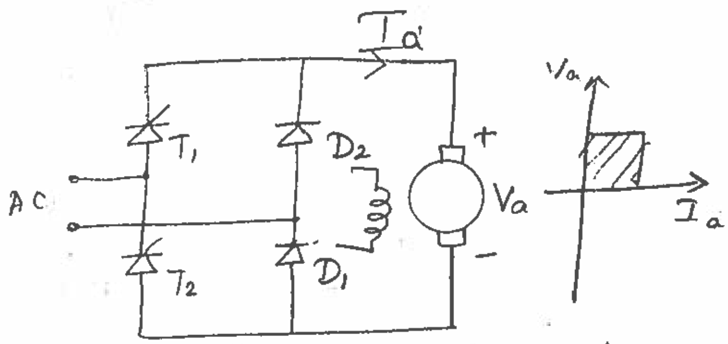
CONTROLLED RECTIFIER FED DC DRIVES :

Controlled rectifiers are used to get variable dc voltage from an ac source of fixed voltage. Controlled rectifier fed dc drives are also known as Static ward - Leonard drives. 1ϕ fully - controlled rectifier and 3ϕ fully controlled rectifier provide control of dc voltage in either direction and therefore, allow motor control in quadrants I & IV

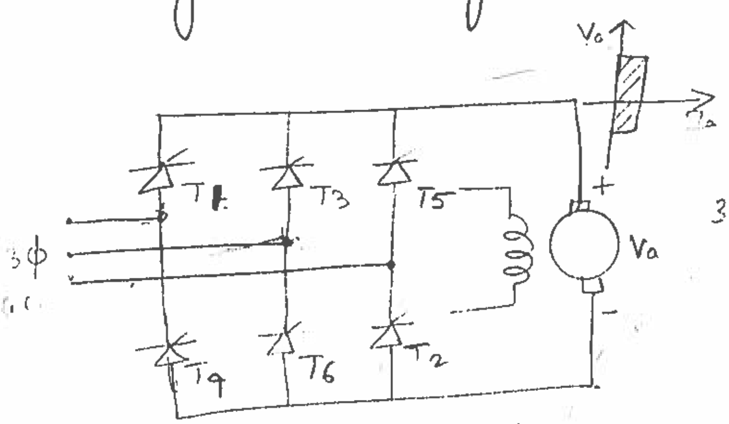
Half controlled rectifiers allow dc voltage control only in one direction and motor control in quadrant I only. For low power applications, single phase rectifier drives are employed. For high power applications, 3-ϕ rectifier drives are used.



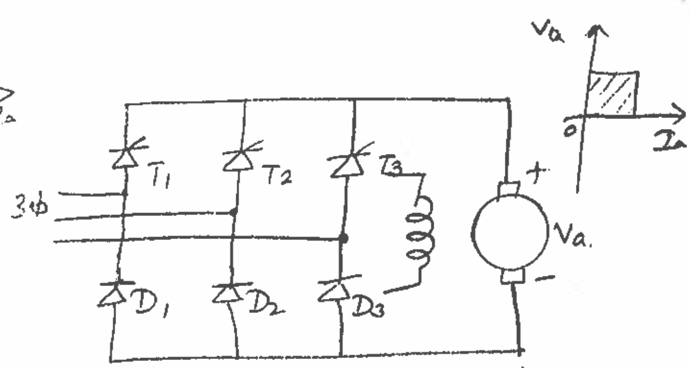
(a) Single-phase fully Controlled



(b) 1ϕ half controlled.



c) 3ϕ fully controlled rectifier

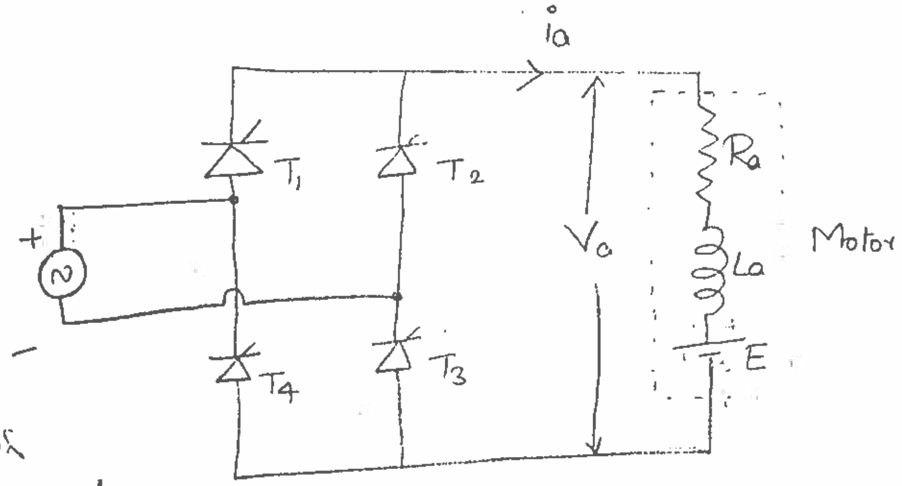


(d) 3ϕ half-controlled rectifier.

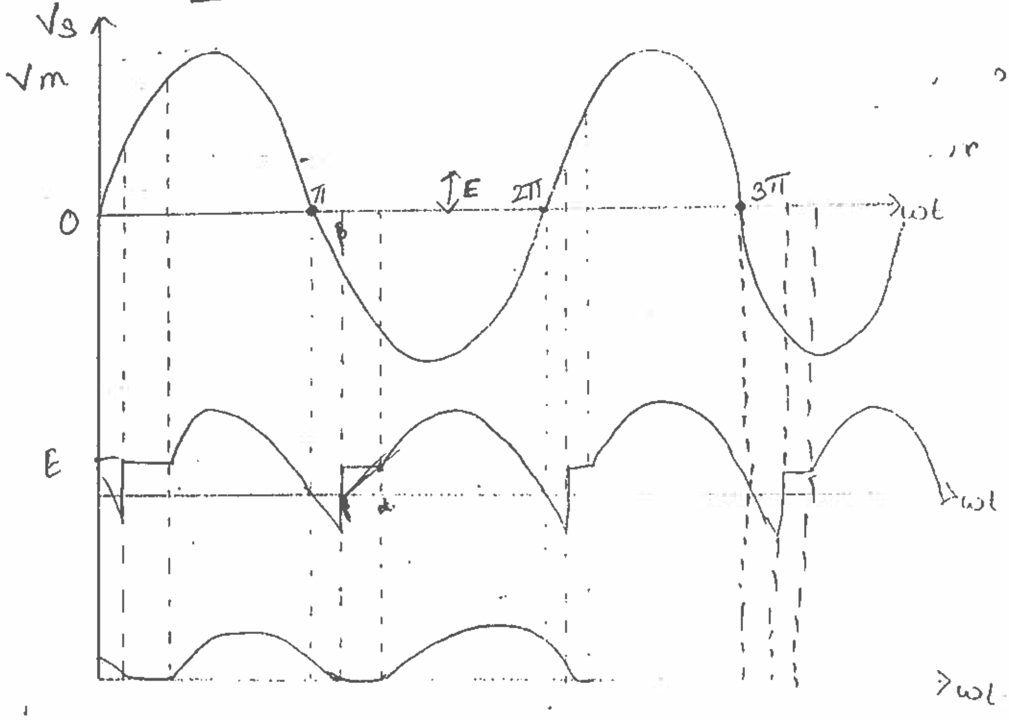
1φ Fully controlled Rectifier Control of dc Separately Excited Motor

For field control, it is fed from a controlled rectifier, otherwise from an uncontrolled rectifier. The ac i/p is defined by,

$$V_s = V_m \sin \omega t$$



(a) Drive circuit



(b) Discontinuous conduction wave forms.

Thyristor T_1 and T_3 are given gate signals from α to π, and thyristors T_2 & T_4 are given gate signals from (π+α) to 2π. When armature current does not flow continuously, the motor is said to operate in discontinuous conduction. When current flows continuously, the conduction is said to be continuous.

In discontinuous conduction mode, current starts flowing with the turn-on of thyristors T_1 and T_3. Motor gets connected to the source and its terminal voltage equals V_s. Current flows after $\omega t = \pi$, and falls to zero at β. Due to absence of current T_1 and T_3 is turned off.

When thyristors T_2 and T_4 are fired at $(\pi+\alpha)$ next cycle of the motor terminal v/g V_a starts.

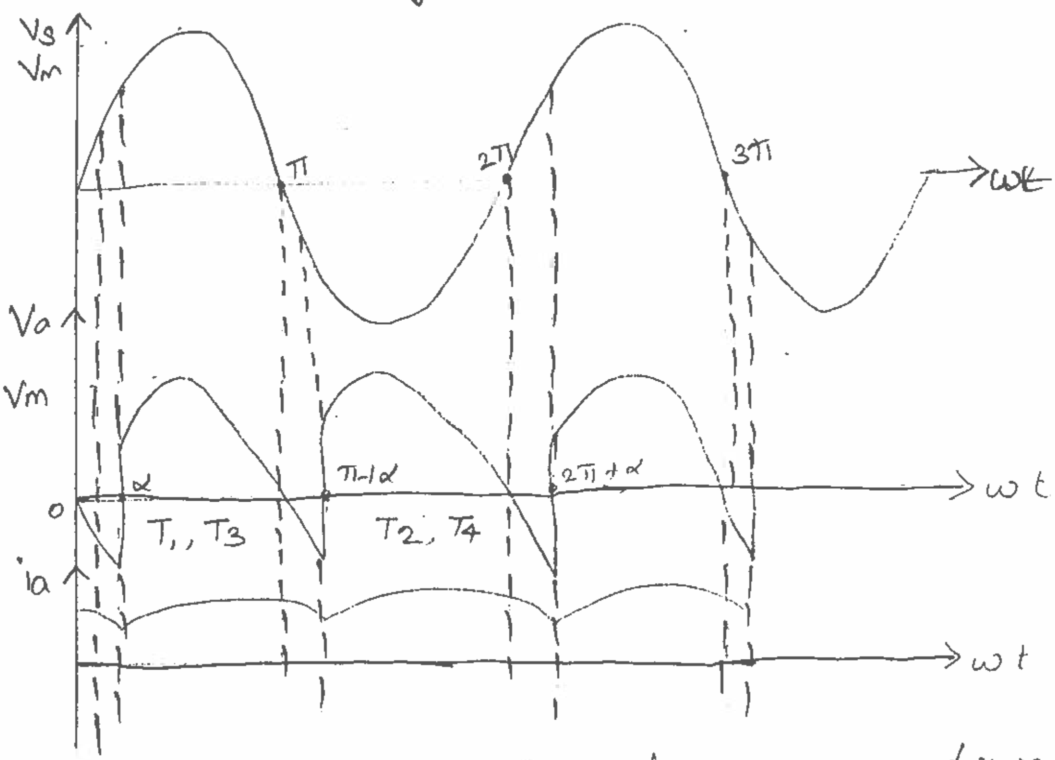
$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E = V_m \sin \omega t \quad , \text{for } \alpha \le \omega t \le \beta$$

$$V_a = E \quad \text{and} \quad i_a = 0 \quad , \text{for } \beta \le \omega t < \pi+\alpha$$

$$V_a = \frac{1}{\pi}\left[\int_{\alpha}^{\beta} V_m \sin \omega t \, d\omega t + \int_{\beta}^{\pi+\alpha} E \, d\omega t\right]$$

$$V_a = \frac{1}{\pi}\left[V_m (\cos\alpha - \cos\beta) + (\pi+\alpha-\beta)E\right]$$

In continuous conduction mode, a positive current flows through the motor and T_2 and T_4 are in conduction just before α. Gate pulses are given to T_1 and T_3 at α. Conduction of T_1 & reverse biases T_2 and T_4 and turns them off. V_a is completed (cycle) when T_2 & T_4 are turned on at $(\pi+\alpha)$ causing turn-off of T_1 & T_3.



(C) Continuous conduction waveform.

$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \; d\omega t$$

$$= \frac{V_m\left[\cos\alpha - \cos(\pi+\alpha)\right]}{\pi}$$

$$\boxed{V_a = \frac{2V_m}{\pi}\cos\alpha}$$

PROBLEM :

A 200 V, 875 rpm, 150 A separately excited dc motor has an armature resistance of 0.06 Ω. It is fed from a single phase - fully controlled rectifier with an ac source voltage of 220V, 50Hz. Assuming continuous conduction, calculate.

* firing angle for rated motor torque and 750 rpm.
* firing angle for rated motor torque and −500 rpm.
* Motor speed for $\alpha = 160^\circ$ and rated torque.

Soln:

$$E = V - I_a R_a$$

$$= 200 - (150)(0.06) = 191V$$

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

$$\frac{E_1}{191} = \frac{750}{875}$$

$$E_1 = \frac{750}{875} \times 191$$

* **E at 750 rpm**

$$E = \frac{750}{875} \times 191$$

$$\boxed{E = 163.7\,V}$$

$$V_a = E + I_a R_a = 163.7 + 150(0.06)$$

$$\boxed{V_a = 172.7\ V}$$

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

$$172.7 = \frac{2(220\sqrt{2})}{\pi} \cos\alpha$$

$$\cos\alpha = 0.872$$

$$\boxed{\alpha = 29.3^\circ}$$

* At -500 rpm

$$E = \frac{-500}{875} \times 191 = -109\ V$$

$$V_a = E + I_a R_a$$

$$= -109 + (150)(0.06)$$

$$= -100V$$

$$V_a = \frac{2V_m}{\pi} \cos\alpha \Rightarrow \cos\alpha = -0.5$$

$$\boxed{\alpha = 120^\circ}$$

* At $\alpha = 160^\circ$

$$V_a = \frac{2V_m}{\pi}\cos\alpha = \frac{2 \times 220\sqrt{2}}{\pi} \cos 160^\circ$$

$$V_a = -186V$$

$$V_a = E + I_a R_a$$

$$-186 = E + 150(0.06)$$

$$E = -195\ V$$

$$\text{Speed} = \frac{-195}{191} \times 875 = -893.2\ \text{rpm.}$$

Problem : 2

The speed of a 10 hp, 220V, 1200 rpm separate excited dc motor is controlled by a 1ϕ full conver The rated armature current is 40 A. The armature resistance is 0.25Ω. The ac supply voltage is 230 V. The motor constant $K_a\phi = 0.18$ V/rpm. Assume that the motor current is constant and ripple free. For a firing angle of 30° and rated motor current, determine the following:

(a) Speed of the motor.
(b) motor torque
(c) Power supplied to the motor.

Given:

Power = 10 hp, Motor vg = 220V, Speed = 1200 rpm
I_a = 40 A, R_a = 0.25 Ω, $k_a\phi$ = 0.18 V/rpm, α = 30°

(a) $$V_a = \frac{2V_m}{\pi}\cos\alpha$$

$$= \frac{2\sqrt{2}\times 230}{\pi}\cos 30° = 179.33\,V$$

$$E_b = V_a - I_aR_a = 179.33 - 40(0.25) = 169.33\,V$$

$$E_b = k_a\phi N$$

$$N = \frac{E_b}{k_a\phi} = \frac{169.33}{0.18} = 940.72 \text{ rpm.}$$

$$\omega_m = \frac{940.72\times 2\pi}{60} = 98.51 \text{ rad/sec.}$$

(b) Motor torque (T) $= k_a\phi I_a$
$= 0.18 \times 40$
$= 7.2$ N-m

(c) Power supplied to motor

$$P = V_a I_a = 179.33\times 40 = 7173.2\,W$$

Problem :

A 1ϕ fully controlled thyristor bridge converter, operating from 230V, 50 Hz mains supplies the arm of a separately excited dc motor running at a speed of 1000 rpm. The motor has an armature resistance of $0.5\,\Omega$ and a back emf constant of 0.1 V/rpm. Assuming continuous current operation for a firing angle of 30°. Estimate the average armature current and the torque developed by the motor.

Given : $V_s = 230V$, $N = 1000$ rpm, $R_a = 0.5\,\Omega$,

$K_a\phi = 0.1$ V/rpm, $\alpha = 30°$

Soln :

$$V_a = \frac{2V_m}{\pi}\cos 30° = \frac{2\times\sqrt{2}\times 230}{\pi}\cos 30°$$

$$= 179.33V$$

$$V_a = E_b + I_a R_a$$

$$179.33 = \underbrace{K_a\phi}\, N + I_a R_a$$

$$179.33 = 0.1\times 1000 + I_a \times 0.5$$

$$\boxed{I_a = 158.66 \text{ A}}$$

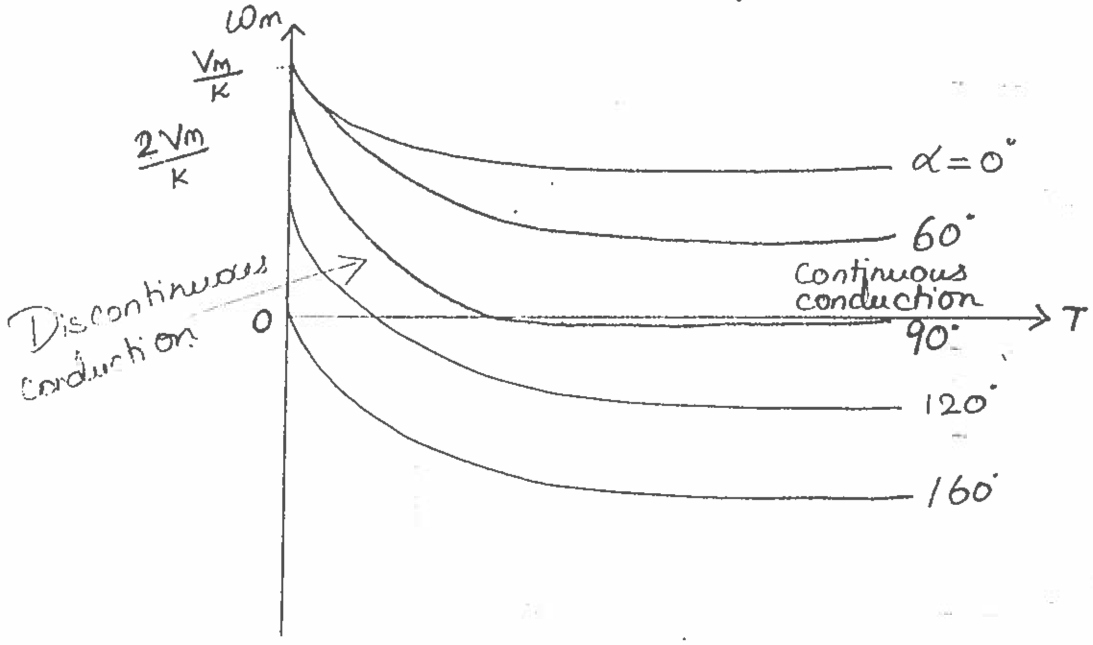
$$T = K_a\phi I_a$$

$$= 0.1 \times 158.66$$

$$= 15.866 \text{ N-m}.$$

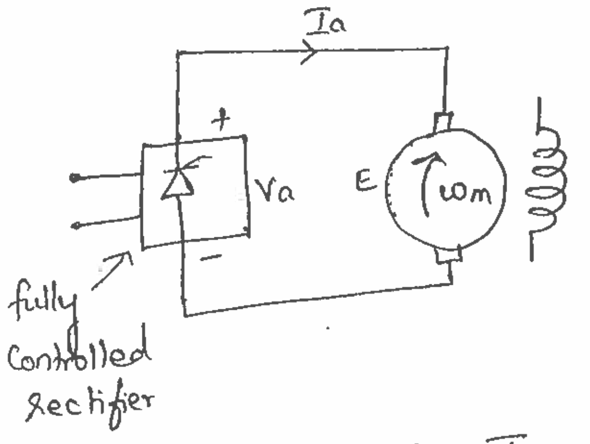
$$\boxed{T = 15.866 \text{ Nm}}$$

Speed - Torque characteristics of 1ϕ fully Controlled Rectifier fed dc separately excited motor.



The drive operates in quadrants I & IV ie, forward motoring and reverse regenerative braking.

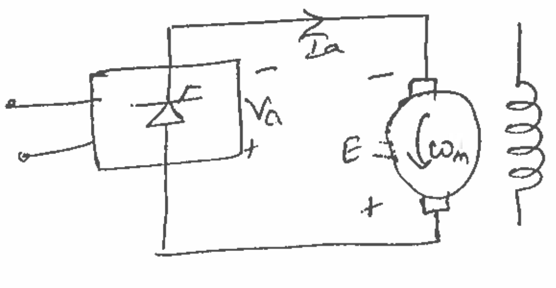
When working in quadrant I, ω_m is +ve and $\alpha \leq 90°$. The polarities of V_a & E are,



Operates in I quadrant (forward motoring)

$\alpha < 90°$, $\omega_m > 0$

Polarities of E, I_a & V_a for quadrant IV operation are

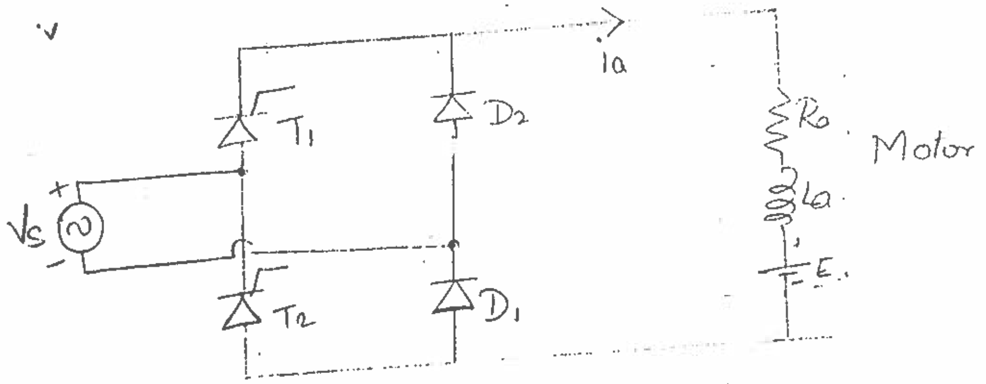


$\alpha > 90°$ & $\omega_m < 0$

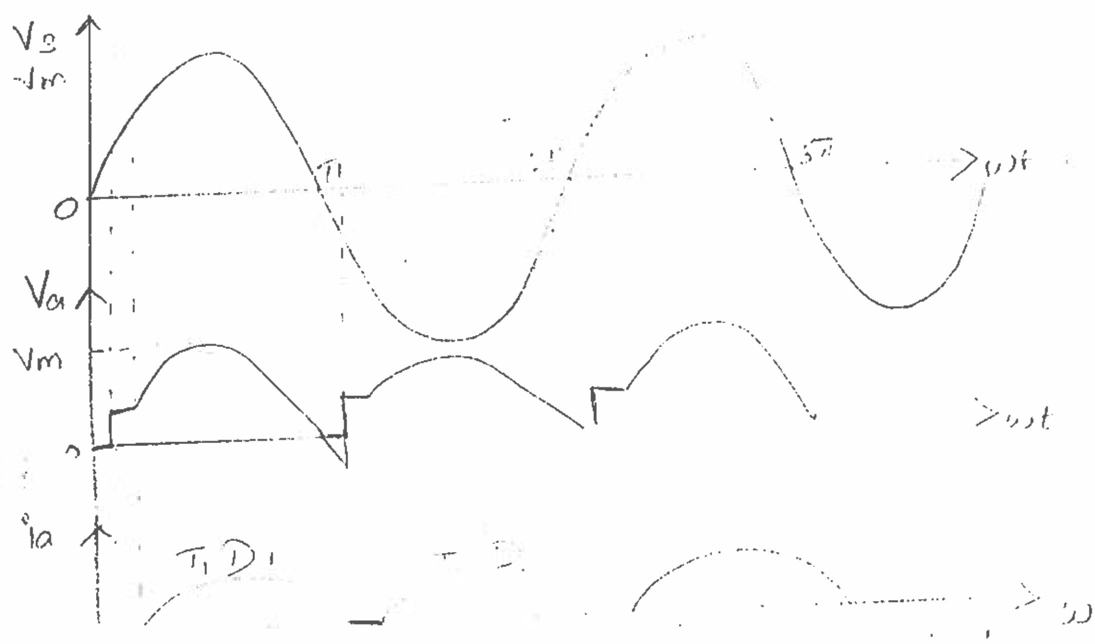
Regenerative braking

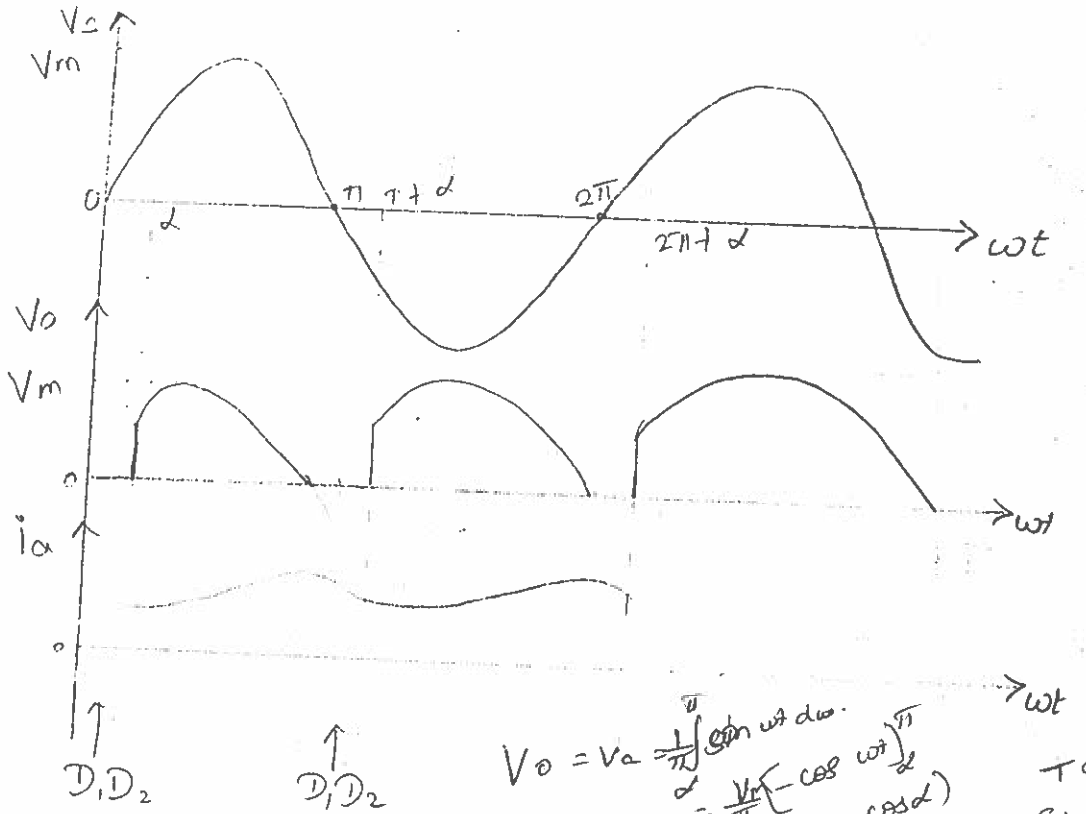
E has reversed due to the reversal of ω_m. Since I_a is still in same direction, machine is working as a generator producing braking torque, further due to $\alpha > 90°$, V_a is −ve. Now rectifier takes power from dc and give it to ac mains. Hence the rectifier is said to operate as a inverter. Since the generated power is supplied to the source in this operation, it is regenerative braking.

SINGLE-PHASE HALF CONTROLLED RECTIFIER CONTROL OF DC SEPARATELY EXCITED MOTOR:



(a) Drive circuit.





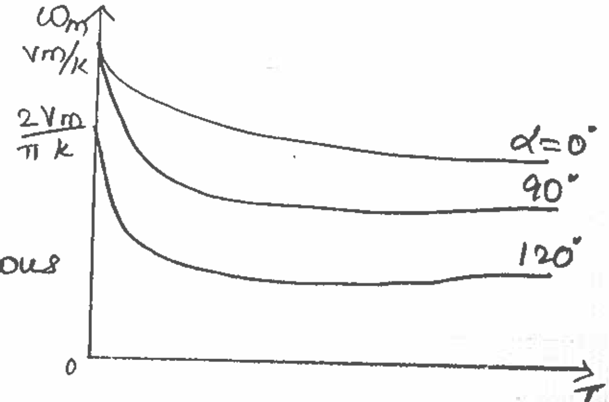
$V_o = V_a = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t$
$= \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$
$= \frac{V_m}{\pi}(1+\cos\alpha)$

$T \propto I_a = K_m I_a$
$E_b \propto \phi\,\omega_m$
$E_b = K_m \omega_b.$

(c) Continuous conduction waveforms.

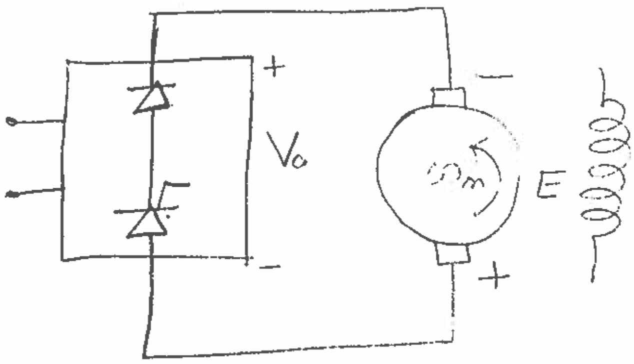
T_1 receives gate pulse from α to π and T_2 from $(\pi+\alpha)$ to 2π. In discontinuous conduction mode, when T_1 is fired at α, motor gets connected to the source through T_1 & D_1 and $V_a = V_s$. The armature current flows and D_2 gets forward biased at π. I_a freewheels through path formed by D_1 & D_2 and motor terminal voltage is zero. Conduction of D_2 reverse biases T_1 & turns it off. I_a is zero at β and remains zero until T_2 is fired at $\pi+\alpha$

The drive operates in quadrant I only. For continuous conduction operation, the o/p voltage can't be reversed.



Speed - torque curve

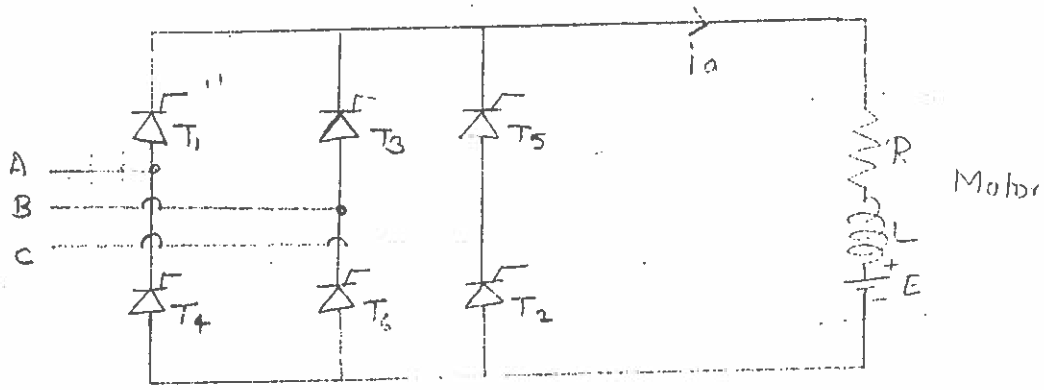
When coupled to an active load, the motor speed can reverse, reversing E as shown below

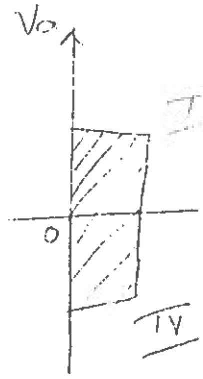


for any α, $V_m < 0$

Now, the current direc is not changed hence m/c works as a generator producing braking torque. Since rectifier voltage could not reverse, genera energy cannot be transferre to ac source, and therefore, it is absorbed in the armature circuit resistance. Braking so obtained is ca plugging (reverse voltage braking). Such a brakin is not only inefficient but it causes large curre to flow through the rectifier and motor. So it may damage the rectifier & motor.

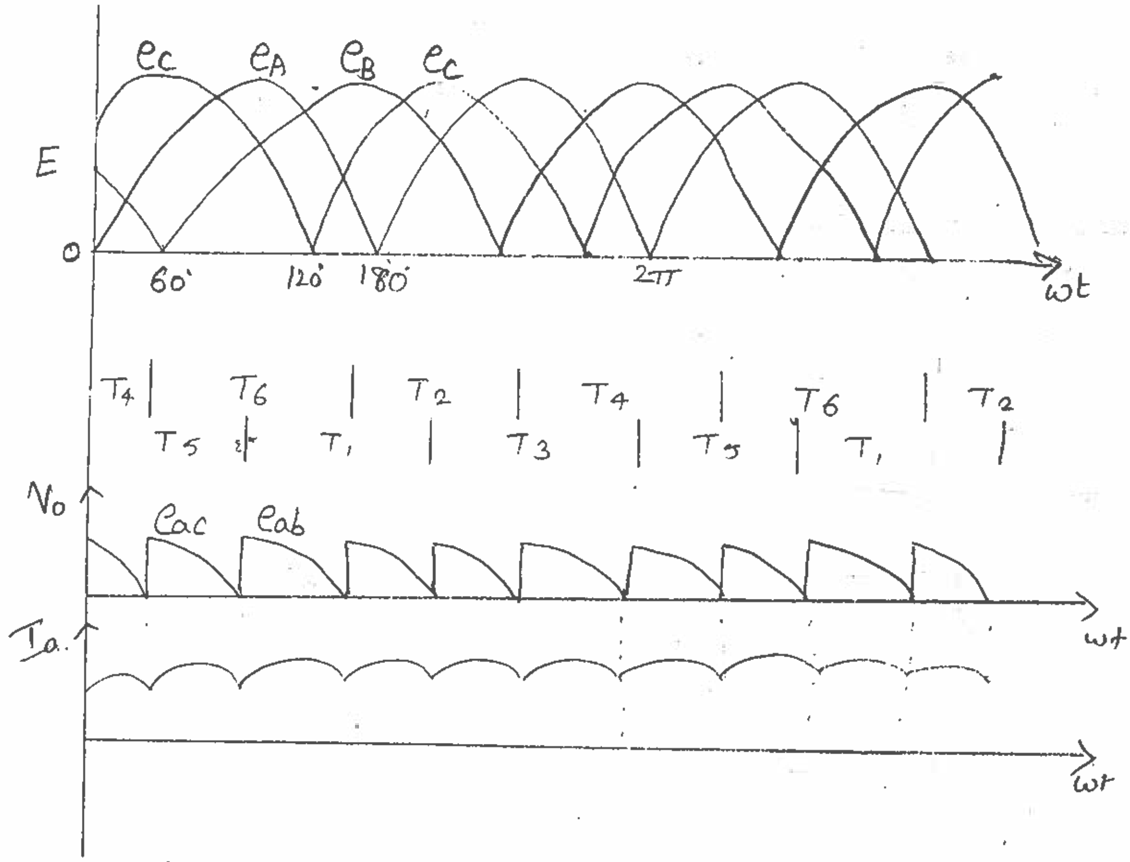
THREE PHASE FULLY-CONTROLLED RECTIFIER CONTRO OF DC SEPARATELY EXCITED MOTOR :





(a) Drive circuit

3-φ controlled rectifiers are used for large power dc motor drives. Thyristors are fired in the sequence of their numbers with a phase difference of 60°. by gate pulses of 120° duration. Each thyristor conducts for 120°, and two thyristors conduct at a time. One from upper group and other from lower group, applying respective line voltage to the motor.



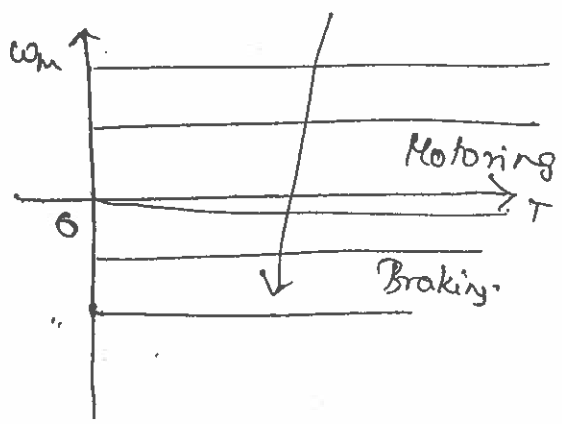
The firing sequence is 12, 23, 34, 45, 56, 61. Since the SCRs are triggered at a faster rate, the motor current is mostly continuous. Therefore the filtering requirement is less than that in the semiconverter system.

For motor terminal voltage cycle from

$\alpha + \pi/3$ to $\alpha + 2\pi/3$

$$V_a = \frac{3}{\pi} \int_{\alpha+\pi/3}^{\alpha+2\pi/3} V_m \sin \omega t \, d(\omega t)$$

$$\boxed{V_a = \frac{3}{\pi} V_m \cos \alpha}$$



quadrant of operation I & L

$$\boxed{\omega_m = \frac{3 V_m}{\pi k} \cos \alpha - \frac{R}{k}}$$

PROBLEM :

A 220 V, 1500 rpm, 50 A separately excited with armature resistance of 0.5 Ω is fed from a 3-φ fully controlled rectifier. Available ac source a line voltage of 440V, 50 Hz. A Y-Δ connecte transformer is used to feed the armature so the motor terminal voltage equals rated voltage Converter firing angle is zero.

→ Calculate transformer turns ratio

→ Determine α when

a) motor is running at 1200 rpm & T_{rat}

b) motor is running at − 800 rpm & twic T_{rate}

$$V_a = \frac{3}{\pi} V_m \cos\alpha$$

$$V_m = \frac{V_a}{\cos\alpha} \cdot \frac{\pi}{3}$$

when $\alpha = 0^\circ$

$$V_m = \frac{\pi}{3} \cdot \frac{220}{\cos 0^\circ} = 230.4\ V$$

$$230.4/\sqrt{3} = 162.9\ V$$

For Y-Δ T/F, $\frac{440/\sqrt{3}}{162.9} = 1.559$

(ii) a) At 1500 rpm,

$$E = V - I_a R_a$$
$$= 220 - (0.5)(50) = 195\ V$$

At 1200 rpm,

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

$$E_1 = \frac{1200}{1500} \times 195 = 156\ V$$

$$\therefore V_a = E + I_a R_a = 156 + (50)(0.5)$$
$$= 181\ V$$

$$V_a = \frac{3}{\pi} V_m \cos\alpha$$

$$\cos\alpha = \frac{\pi}{3} \cdot \frac{V_a}{V_m} = \frac{\pi}{3} \times \frac{181}{230.4} = 0.8227$$

$$\boxed{\alpha = 34.65^\circ}$$

(b) At −800 rpm,

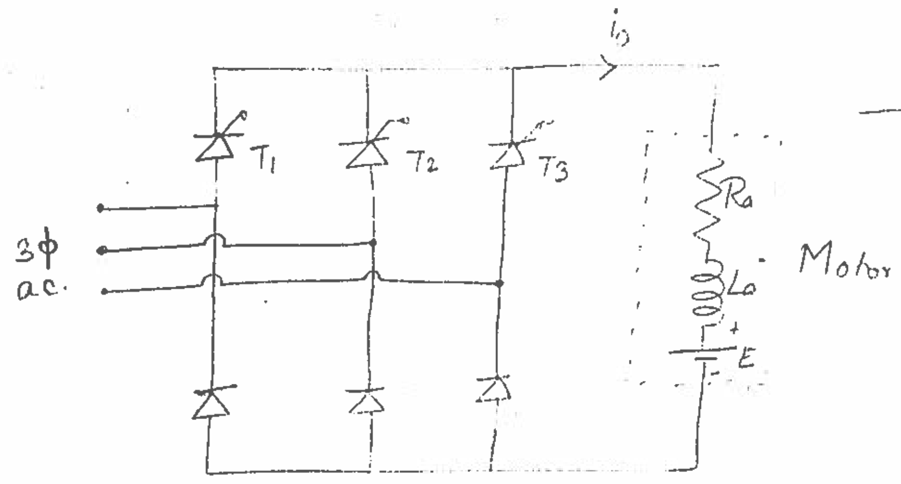
$$E = \frac{-800}{1500} \times 195 = -104\ V$$

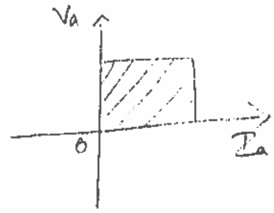
$$V_a = E + I_a R_a = -54\ V$$

$$\therefore \cos\alpha = \frac{\pi}{3} \cdot \frac{V_a}{V_m} = \frac{\pi}{3} \times \frac{-54}{230.4} = -0.2454$$

$$\boxed{\alpha = 104.20^\circ}$$

3-φ Half Controlled Rectifier :





$$V_a = \frac{3V_m}{2\pi}(1+co$$

$$\omega_m = \frac{3V_m}{2\pi k}(1+\cos$$

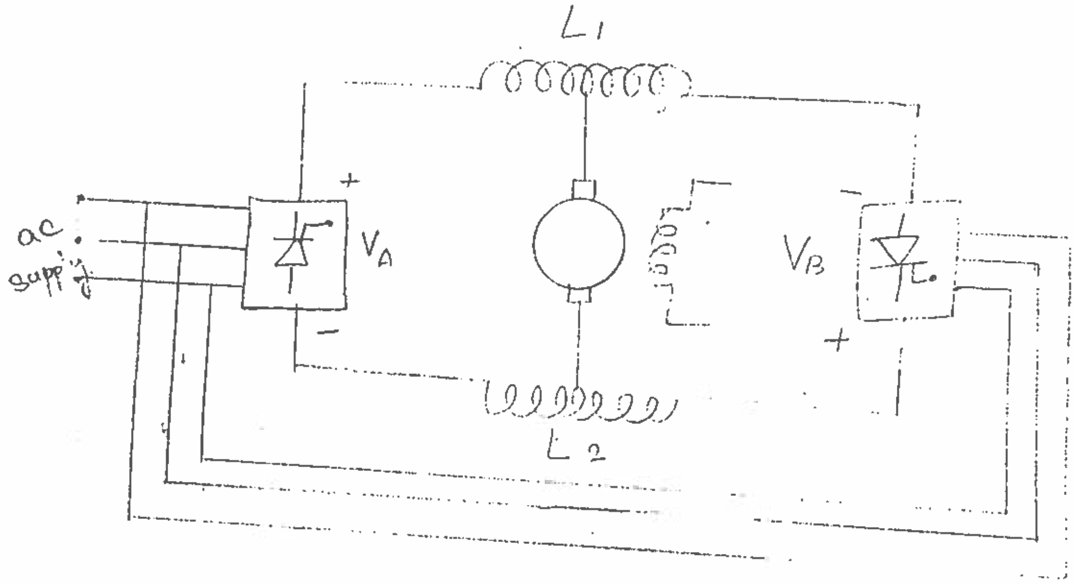
$$- \frac{R_a}{k^2}$$

DUAL CONVERTER :

It consists of two fully-controlled rectifiers connected in anti-parallel across the armature. Upto 10 kW → 1φ fully controlled rectifiers can be used. For higher ratings → 3φ fully controlled rectifiers are employed.

Rectifier A → Provides +ve motor current
(Motor control in I & IV) voltage → +ve & −ve

Rectifier B → −ve current & voltage in either direct
(Motor control in III & II)



Advantages :

→ Efficient four quadrant operation.
→ In intermittent load application it prevents load torque fluctuations.
→ A wide range of speed control is possible.

Drawbacks :

* High initial cost
* Low efficiency (Two additional m/c of same rating as that of main motor)
* Requires frequent maintenance
* More noise
* Large weight and size.
* Costly foundation and a large amount of space is required.

PROBLEMS :

* A 120 V, dc shunt motor has an armature resistance of 0.2 Ω & a field resistance of 60 Ω. It runs at 1800 rpm. taking a full load current of 40 A. Find the speed on half load condition

$V = 120\,V$, $R_a = 0.2\,\Omega$, $R_{sh} = 60\,\Omega$

$I_{L1} = 40\,A$, $N_1 = 1800$ rpm.

For shunt motor, $I_{sh} = \frac{V}{R_{sh}} = \frac{120}{60} = 2A$

$$I_{a1} = I_{L1} - I_{sh}$$

For full load, $I_{a1} = 40 - 2 = 38\,A$

$$E_{b1} = V - I_{a1} R_a = 120 - 38(0.2) = 112.4\ V$$

For half load ; $T_2 = \frac{1}{2} T_1$

$$T \propto \phi I_a \quad (\phi \rightarrow \text{Constant})$$

$$\frac{T_1}{T_2} = \frac{I_{a1}}{I_{a2}}$$

$$\frac{T_1}{0.5 T_1} = \frac{38}{I_{a2}}$$

$$\boxed{I_{a2} = 19\ A}$$

$$E_{b2} = V - I_{a2} R_a = 120 - 19(0.2) = 116.2\ V$$

$N \propto E_b$ when ϕ is constant.

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}}$$

$$\frac{1800}{N_2} = \frac{112.4}{116.2}$$

$$\boxed{N_2 = 1860.85\ \text{rpm}}$$

PROBLEM :

A 250 V dc Shunt motor has $R_a = 0.08\ \Omega$ when connected to 250V d.c. supply it develops back emf of 242 V at 1500 rpm. Determine

- → Armature current
- → Armature current at Start
- → Back emf if arm. current is changed to 120 A
- → The speed of the machine if it is operated as a generator in Order to deliver an armature Current of 87 A at 250V.

Given:

$R_a = 0.08\,\Omega$, $E_{b1} = 242\,V$, $V = 250\,V$

(i) $V = E_{b1} + I_{a1} R_a$

$250 = 242 + I_{a1}(0.08)$

$\boxed{I_{a1} = 100\,A}$

(ii) At start : $N = 0$ $\therefore E_b = 0$

$I_a(\text{start}) = \frac{V}{R_a} = \frac{250}{0.08} = 3125\,A$

(iii) If $I_{a2} = 120\,A$

$E_{b2} = V - I_{a2} R_a$

$= 250 - (120)(0.08)$

$E_{b2} = 240.4\,V$

(iv) Induce emf as a generator be Eg.

$E_g = V + I_a R_a$

$= 250 + 87.(0.08)$

$E_g = 256.96\,V$

In both the case M or G $E \propto N\phi$

As flux is constant, $E \propto N$

$\frac{E_b}{E_g} = \frac{N_m}{N_g}$

$\frac{242}{256.97} = \frac{1500}{N_g}$

$N_g = 1592.7$ rpm.

Methods :-

* Simultaneous control or Circulating current control
* Non-Simultaneous control or non-circulating current control

In simultaneous control both the rectifiers are controlled together

$$V_A + V_B = 0$$
$$\cos \alpha_A + \cos \alpha_B = 0$$
$$\alpha_A + \alpha_B = 180°$$

Inductor L_1 & L_2 are added to reduce ac circulating current. Because of the flow of ac circulating current simultaneous control is also known as circulating current control. Inductor are chosen to allow a circulating current of 30% of full load current. This completely eliminates discontinuous conduction.

* Non simultaneous mode → Non-circulating current Control method.

One rectifier is controlled at a time. Non current flow and L_1 & L_2 are not needed.

<u>Simultaneous</u> :- In quadrant I, Rectifier A will be rectifying $0 < \alpha_A < 90°$ and Rectifier B will be inverting $90° < \alpha_B < 180°$ for speed reversal α_A is increasing α_B is decreasing to satisfy $\alpha_A + \alpha_B = 180$ V_A & V_B, I_a shifts to the emf exceeds magnitude of rectifier B & the motor operate in quadrant II.

Non - Simultaneous :-

Quadrant I rectifier A will be supplying the motor & B will not be operating. $\alpha_A \rightarrow$ set to highest value. Rectifier works as inverter and forces the I_a to zero. Then firing pulses are given to rectifier B.

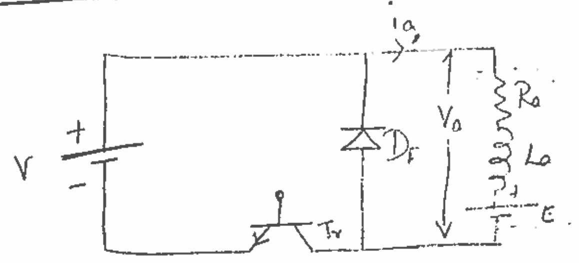
DC CHOPPER DRIVE :

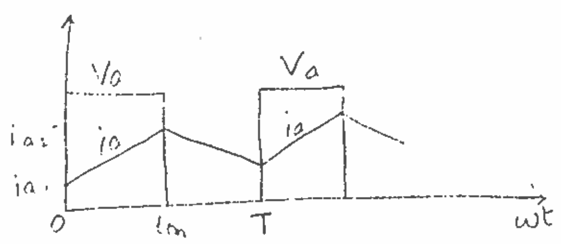
Chopper :- It is commonly known as dc-dc converter, used to get variable dc voltage from a dc source of fixed voltage.

Advantages over controlled rectifier :

* Operation at high frequency improves motor performance by reducing current ripple, reduce machine losses, eliminating discontinuous conduction hence it improves speed regulation.
* High efficiency
* flexibility in control
* Small size
* quick response
* Light weight

CHOPPER CONTROL OF SEPARATELY EXCITED DC MOTOR





MOTORING CONTROL

During on period, $0 \le t \le t_{on}$, $V_a = V_s$

$$i_a R_a + L_a \frac{di_a}{dt} + E = V_s \quad \text{——— (1)}$$

During OFF period $t_{on} \le t \le T$

$$R_a i_a + L_a \frac{di_a}{dt} + E = 0 \quad \text{——— (2)}$$

$$V_a = \frac{1}{T} \int_0^{t_{on}} V_s \, dt = \frac{V_s}{T} [t]_0^{t_{on}} = V_s \frac{t_{on}}{T}$$

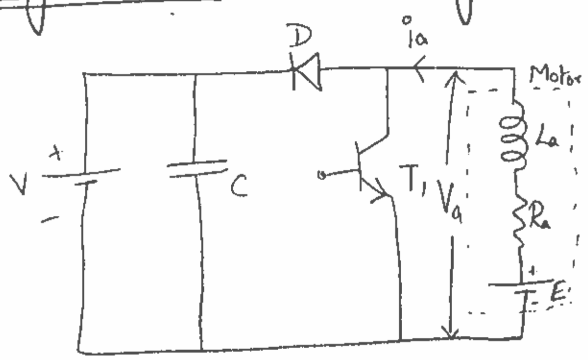
$$\boxed{V_a = V_s \, \delta} \quad \text{——— (3)} \quad \text{when } \delta = \frac{\text{Duty interval}}{T} = \frac{t_{on}}{T}$$

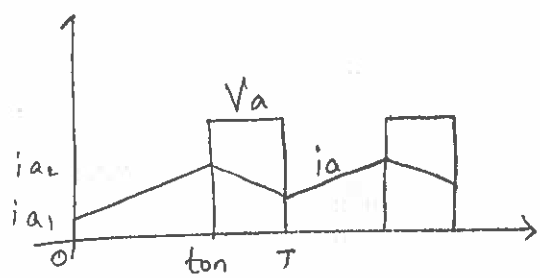
$$E = V_a - I_a R_a$$

$$I_a = \frac{\delta V_a - E}{R_a} \quad \text{——— (4)}$$

$$\omega_m = \frac{\delta V}{K} - \frac{R_a}{K^2} T \quad \text{——— (5)}$$

Regenerative Braking :





During energy storage interval $0 \le t \le t_{on}$, $V_a = 0$

$I_a \uparrow$ from I_{a1} to I_{a2}

During duty interval $t_{on} \le t \le T$ motor terminal vtg V_a

armature current decreases from I_{a2} to I_{a1}

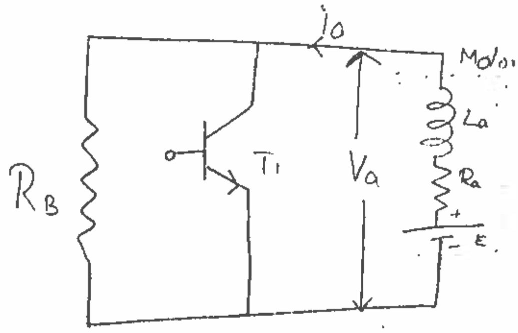
$$V_a = \frac{1}{T}\int_{t_{on}}^{T} V_s \, dt = \frac{V_s}{T}\left[t\right]_{t_{on}}^{T} = \frac{V_s}{T}\left[T - T_{on}\right]$$

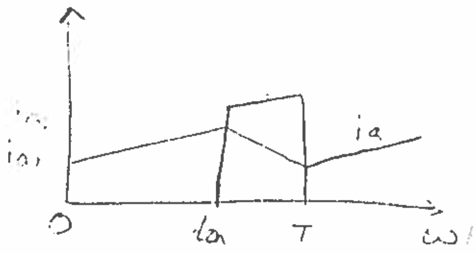
$$\boxed{V_a = (1-\delta)V_s}$$

$$E = k\omega_m \quad \text{--- (2)}$$

$$\Rightarrow I_a = \frac{E - \delta V}{R_a} \quad \text{--- (4)} \qquad T = -kI_a \quad \text{--- (3)}$$

DYNAMIC BRAKING





During $0 \le t \le t_{on}$ $i_a \uparrow$ from i_{a1} to i_{a2}. A part of generated energy is stored in inductance and rest is dissipated in R_a and Tr.

During $t_{on} \le t \le T$ $I_a \downarrow$ from I_{a2} to I_{a1}, stored energy dissipated in braking resistance R_B & R_A

CONTROL STRATEGIES:

The average o/p v/g can be controlled through c

1. Time Ratio Control (TRC)
2. Current limit Control (CLC)

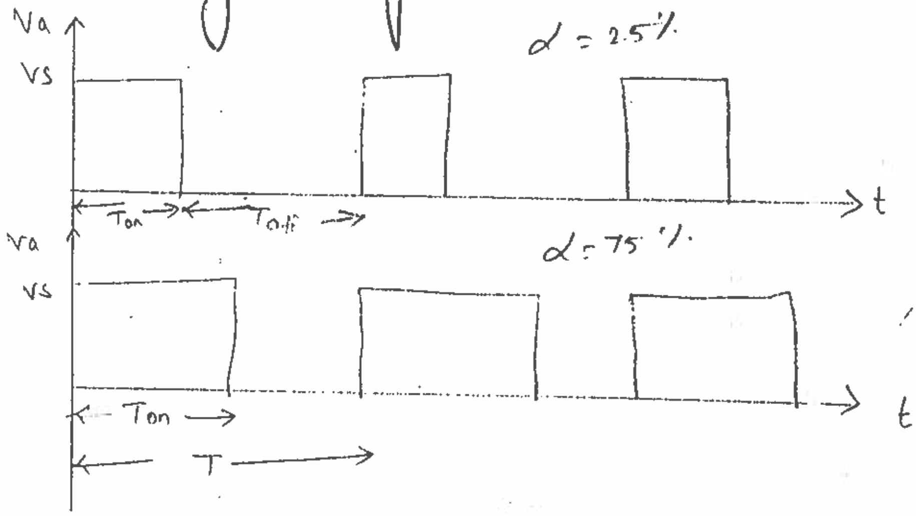
Time Ratio Control:

The value of $\frac{T_{ON}}{T}$ is varied in two ways.

* Constant frequency system
* Variable frequency system

* Constant frequency System:

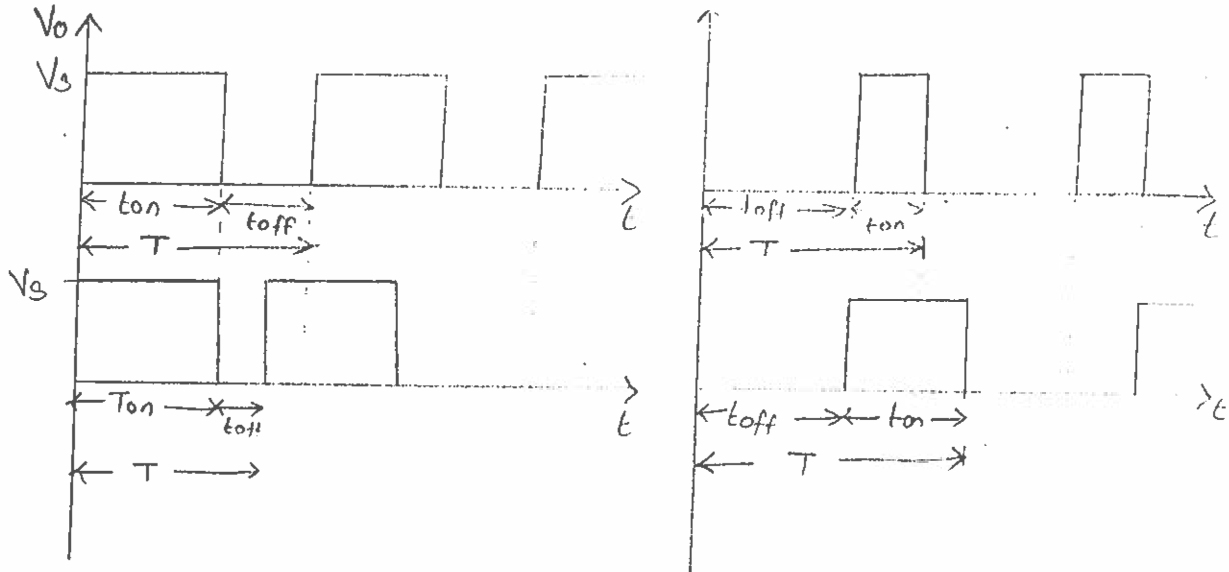
Ton → Varied but chopping frequency is kept constant. The width of pulse is varied by using PWM technique.



α can be varied from zero to unity. Therefore output voltage can be varied between 0 to Vs. The constant frequency control gives low ripple and requires smaller size of filter and has fast response. This is preferred for chopper drives.

* Variable frequency System:

Here T (or) f is varied and either Ton (or) Toff is kept constant. This type of controlling α is called frequency modulation scheme. Ton is constant, T is varied.

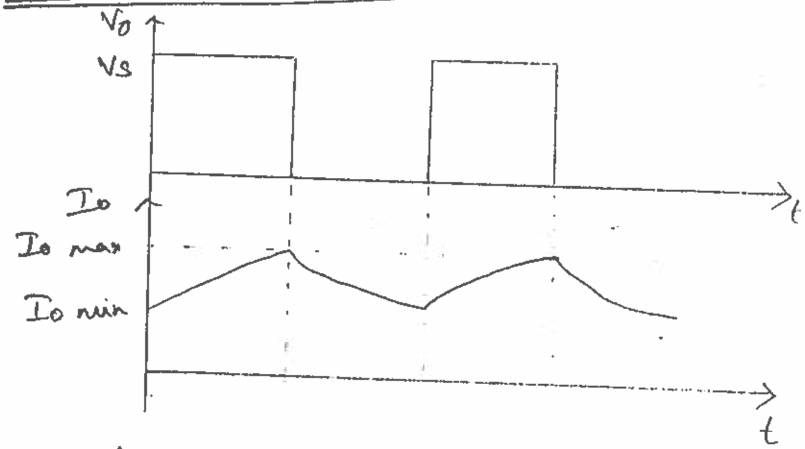


(a) Ton constant (b) Toff constant

Disadvantages :

* For wide range of frequency variation the filter design is difficult.
* Generates harmonics, unpredictable frequencies which may produce interference with signalling & telephone lines.
* Large Toff makes I_L discontinuous.

Current Limit Control (CLC)



Chopper is switched ON & OFF so that the current in the load is maintained b/w Iomin to Iomax

ON → when $I_o = I_{o\,min}$

OFF → when $I_o = I_{o\,max}$

Used for both constant and variable frequency system. CLC is used only when load has energy storage element.

Problem : (1)

The speed of a 50 kW, 500V, 120 A, 1500 rpm separately excited d.c motor is controlled by a 3ϕ full converter fed from 400V, 50 Hz supply. Motor armature resistance is 0.1 Ω. Find the range of firing angle required to obtain speeds between 1000 rpm & −1000 rpm at rated torque.

Given :

$P = 50$ kW , $V_s = 500$ V , $I_a = 120$ A

$N = 1500$ rpm , $R_a = 0.1\ \Omega$

Solution :-

Rated $\rightarrow$ $V_t = E_a + I_a R_a$

$$= K_m \omega_m + I_a R_a$$

$$500 = K_m \times \frac{2\pi \times 1500}{60} + (120 \times 0.1)$$

$$\boxed{K_m = 3.11 \ \text{V-s/rad}}$$

Firing angle at 1000 rpm :

$$V_o = V_t = K_m \omega_m + I_a R_a$$

for 3ϕ full converter

$$V_o = V_t = \frac{3 V_m}{\pi} \cos \alpha$$

$$\frac{3V_m}{\pi}\cos\alpha = K_m\omega_m + I_a R_a$$

$$\frac{3\times400\times\sqrt{2}}{\pi}\cos\alpha = 3.11\times\left(\frac{2\pi\times1000}{60}\right) + 120\times0.1$$

$$540.19\cos\alpha = 337.68$$

$$\cos\alpha = 0.6251$$

$$\boxed{\alpha = 51.3^\circ}$$

Firing angle at -1000 rpm

$$\frac{3V_m}{\pi}\cos\alpha = K_m\omega_m + I_a R_a$$

$$\frac{3\times400\times\sqrt{2}}{\pi}\cos\alpha = 3.1\times\frac{2\pi(-1000)}{60} + 120\times0$$

$$540.19\cos\alpha = -313.68$$

$$\boxed{\alpha = 125.49^\circ}$$

PROBLEM :

A chopper used for ON & OFF control of a dc separately excited motor has supply voltage of 230 V, $T_{ON} = 10$ ms, $T_{OFF} = 15$ ms. Neglecting armature inductance and assuming continuous conduction of motor current. Calculate the average load current when the motor speed is 1500 rpm, has a volt constant $K_v = 0.5$ V/rad/sec. The armature resistance is $2\,\Omega$.

$V_a = \alpha V_s$ (or) δV_s $\qquad$ $\omega_m = 0$ min speed

$\delta V_s = E + I_a R_a$

$\delta \times 220 = K_e \phi \omega_m + I_a R_a$

$= 0.08 \times 0 + 25 \times 0.2$

$= \frac{5}{220}$

$\boxed{\delta = 0.0227}$

For max. speed, $\alpha = 1$ or $\delta = 1$

$1 \times 220 = 0.08 \times N + (25 \times 0.2)$

$\boxed{N = 2687.5 \text{ rpm}}$

$\therefore$ Range of speed control is $0 < N < 2688$ rpm

& corresponding duty cycle is $0.022 < \alpha < 1$

III - 3ϕ INDUCTION MOTOR DRIVES

Speed control of 3ϕ IM : Stator control - Stator voltage and frequency control - AC chopper and Cycloconverter fed IM drives. - Rotor control - Rotor resistance control and slip power recovery schemes - Static control of rotor resistance using DC chopper - Static and Scherbius drives - Introduction to vector Control based drives.

INTRODUCTION :

IM → Constant speed drive
bcoz conventional speed control is expensive or highly inefficient.

DC → Variable speed drive

Disadv. of DC M/c → Presence of commutator and brushes which require frequent maintenance & make them unsuitable for explosive & dirty environments.

Adv. of IM → Squirrel cage IM are rugged, cheaper, ligher, smaller, more efficient, require lower maintenance & can operate in dirty & explosive environment.

Appln. of IM : Fans, blowers, cranes, conveyers, traction etc. Other dominant applications are underground and underwater installations, and explosive and dirty environment.

Analysis of 3ϕ IM at constant frequency :

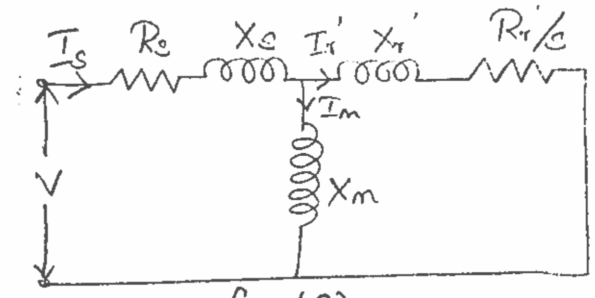


fig (a)

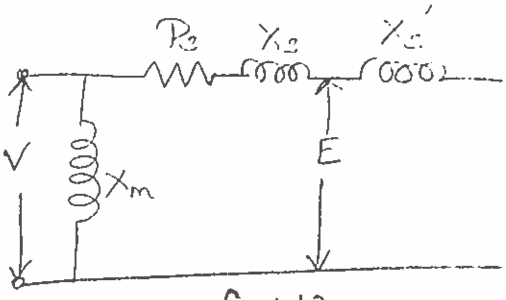


fig (b)

Per - phase equivalent circuit of a 3ϕ IM is s[hown] in fig (a). Since, stator impedance drop is generall[y] negligible compared to terminal voltage V, the equivalent circuit can be simplified to that shown fig. (b.) R_r' and X_r' are the stator referred val[ues] of rotor resistance R_r and rotor reactance X_r.

Slip is defined by

$$S = \frac{N_s - N_r}{N_s} = \frac{\omega_{ms} - \omega_m}{\omega_{ms}} \quad \text{——— (1)}$$

where ω_m and ω_{ms} are rotor and synchronous

$$\omega_{ms} = \frac{120f}{P} \times \frac{2\pi}{60} = \frac{4\pi f}{P} \text{ rad/sec} \quad \text{——— (}$$

where f and P are supply frequency and number of poles respectively.

From eqn (1) $\quad \omega_m = \omega_{ms}(1-s) \quad$ ——— (3)

From fig. (b)

$$I_r' = \frac{V}{\left(R_s + \frac{R_r'}{s}\right) + j\left(X_s + X_r'\right)} \quad \text{——— (4)}$$

Power transferred to rotor (or air-gap power)

$$P_g = 3 I_r'^2 R_r'/s \quad \text{———} \quad (5)$$

Rotor copper loss is

$$P_{cu} = 3 I_r'^2 R_r' \quad \text{———} \quad (6)$$

Electrical power converted into mechanical power

$$P_m = P_g - P_{cu} = 3 I_r'^2 R_r' \left(\frac{1-s}{s}\right) \quad \text{———} \quad (7)$$

Torque developed by motor

$$T = P_m/\omega_m \quad \text{———} \quad (8)$$

Sub eqns (3) and (7) in (8)

$$T = \frac{3}{\omega_{ms}} I_r'^2 \frac{R_r'}{s} \quad \text{———} \quad (9)$$

A comparison of eqns (9) and (5) suggests that

$$T = \frac{P_g}{\omega_{ms}} \quad \text{———} \quad (10)$$

Substituting eqn (4) in (9)

$$T = \frac{3}{\omega_{ms}} \left[\frac{V^2 \, R_r'/s}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2}\right] \quad \text{———} \quad (11)$$

Diff T w.r.to s equating to zero gives the slip for maximum torque.

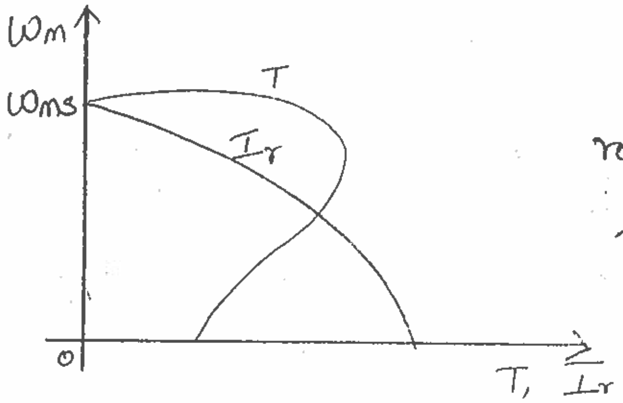
$$S_m = \pm \frac{R_r'}{\sqrt{R_s^2 + (X_s + X_r')^2}} \quad \text{———} \quad (12)$$

Sub (11) in (12) yields an expression for max. torque.

$$T_{max} = \frac{3}{2\omega_{ms}} \left[\frac{V^2}{R_s \pm \sqrt{R_s^2 + (X_s + X_r')^2}}\right] \quad \text{———} \quad (13)$$

Max torque = breakdown torque

$$\therefore \boxed{\frac{T}{T_{max}} = \frac{2}{\frac{s}{s_m} + \frac{s_m}{s}}} \quad (14)$$



Both rotor current and rotor torque are zero at synchronous speed.

Speed control of 3ϕ IM :

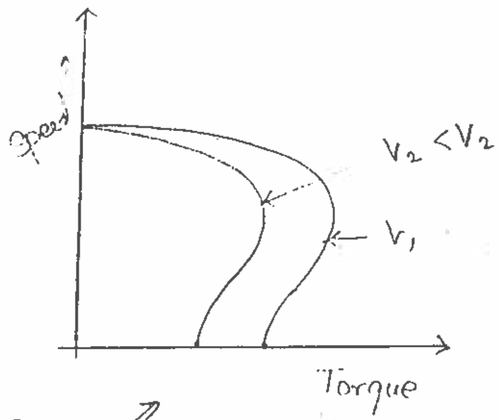
IM speed can be controlled by using power semicon controller.

i) Stator voltage control
ii) Stator frequency control
iii) Variable voltage variable frequency control (V/f.
v) Rotor resistance control
vi) Slip power recovery control

Stator Voltage control :

IM speed can be controlled by varying the stator voltage. This method of speed control is known as stator voltage control. Here the supply frequency is Co

The torque is proportional to the square of its stator voltage i.e. $T \propto V^2$. For the same slip and frequency, a small change in stator voltage results a relatively large change in torque. A 10 % reduction i voltage causes a 19% reduction in developed torque as well as the starting and maximum torques.



This shows two curves for two different values of the stator voltage. Here the slip at the maximum torque remains unchanged since it is not a function of voltage. For a low slip motor, the

speed range is very narrow. So this method is not used for wide range of speed control and constant torque load.

It is an excellent method for reducing starting current and increasing efficiency during light load conditions. The starting current is reduced since it is directly proportional to the square of the voltage. This method is only suitable for speed control below the rated speed.

AC voltage controller for 3-ϕ IM

The stator voltage is controlled in these speed control systems, by means of a power electronic controller. There are two methods of control as follows

a) on-off control
b) phase control

In on-off control, the thyristors are employed as switches to connect the load circuit to the source voltage and then disconnect it for another few cycles. Here thyristor acts as high speed switch (contactor). This method is known as integral cycle control.

In phase control, the thyristors are emplo[yed] as switch connect the load to the ac source for a portion of each cycle of input voltage. The power circuit configuration for on-off control and phase control do not differ in any manner. Normally thyristors in phase control modes are used. The various schemes are

i) 1ϕ or 3ϕ half wave ac vtg controller

ii) 1ϕ or 3ϕ full wave ac vtg controller.

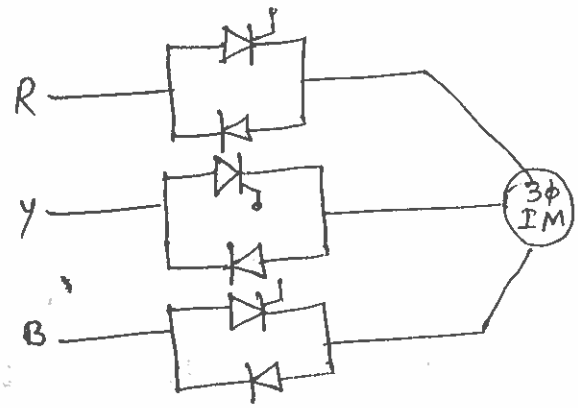


fig (a)

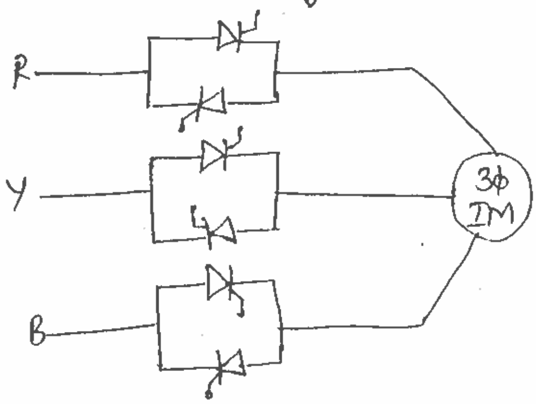


fig (b)

fig (a) and fig (b) shows the circuits of 3ϕ half wave and full wave ac vtg controller for star conn. stators. In half wave ac voltage controller consists of 3 SCRs and 3 diodes. Here one SCR and one diode in antiparallel are connected b/w the line and motor in a phase.

The full wave ac controller consists of 6 SCRs here two SCRs in antiparallel are connected between the line and motor in a phase. The main advantage half wave controller is a saving the cost of semiconductor devices and does not give rise to

Components in any part of the system. The disadvantage is that, it introduces more harmonics into the line current.

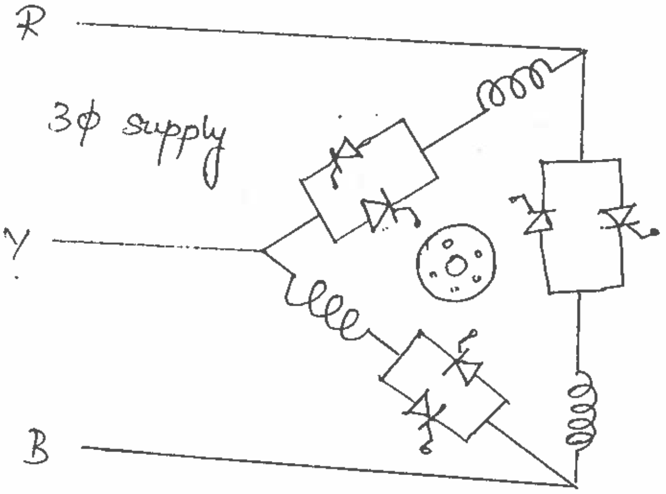


fig (c)

fig (c). shows 3φ full wave ac vg controller for delta connected load. It may be used and has the advantage of reducing the current of the device. When the motor is delta connected, the third harmonic voltages produced by motor back emf causes circulating current through the windings which increases losses and thermal loading of the motor.

For low power rating motors anti-parallel SCR pair can be replaced by a triac. It is shown in fig (d). AC voltage controllers are also used for soft start of motors.

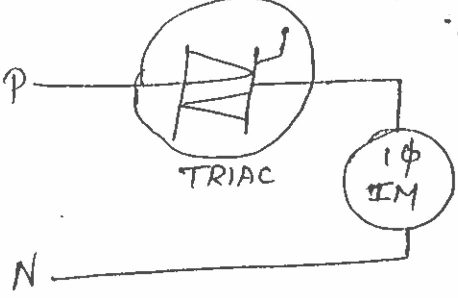


fig (d)

The thyristor controller brings in two more sources of power losses. Power loss takes places in the power devices in the controller. In addition, harmonic losses takes place in the motor due to harmonic current flowing in the winding due to phase control. These the additional loss components will make this spe controller further inefficient. Harmonic currents result, in cogging / craiding etc. For these type of loads, the load torque is directly proportional to speed squared and i/p current is maximum when slip $s = 1/3$.

Advantages:

1. The circuit is very simple.
2. More compact and less weight.
3. Quick response
4. There is a considerable savings in energy and thus it is a economical method.

Disadvantages:

1. The i/p PF is very low.
2. Voltage and current waveforms are highly distorted due to harmonics, which affects the efficiency of the machine.
3. Performace is poor under running condition at low speeds.
4. Operating efficiency is low as resistance losses are high.
5. Maximum torque available from the motor decrea with decrease in stator voltage.
6. At low speeds, motor currents are excessive and special arrangements should be provided to limit the excessive currents.

Voltage / frequency Control

The increase in the supply frequency increases the motor speed and also reduces the maximum torque of the motor. But the increase in voltage results in the maximum torque of the motor.

i) f increases ; N increases ; T_{max} decreases

ii) Voltage increases ; T_{max} increases.

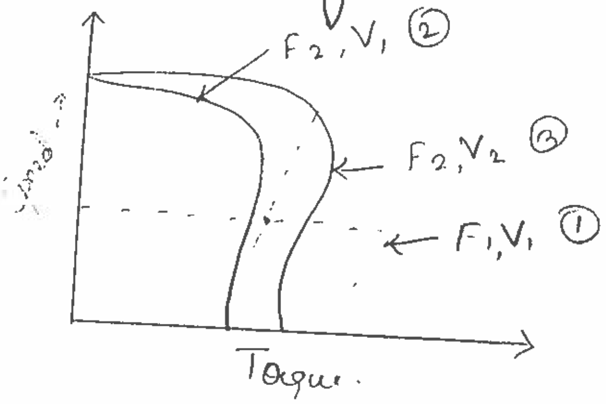


Figure shows three curves for speed - torque characteristics

i) Here, we consider the reference voltage V_1 and frequency f_1. For the fan type load in figure, the reference operating point is 1. It is indicated as curve ①

ii) If we increase the frequency of the supply to f_2 here while keeping the voltage V_1 unchanged, the motor speed increases and the maximum torque decreases. The load larger in this case is higher than the max torque provided by the motor. Thus, no steady - state operating point can be achieved and the motor eventually stalls. It is indicated as a curve ②

iii) Now let us keep the supply frequency to the new value at f_2, but increase the magnitude of the voltage to V_2. The maximum torque increases and a new steady state point is achieved. It is indicated by curve ③

Stator frequency control :-

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

Speed is directly proportional to the frequency ∴ f changes, speed also get changed.

The induced emf in stator wdg

$\phi \rightarrow$ flux /
$K_w \rightarrow$ wdg f
$f \rightarrow$ freq of
$T_1 \rightarrow$ No. of tu
stc

$$V_1 = 2\pi f T_1 \phi K_w$$

If f varied, V_1 is also vary to maintain flux constant.

i) At low frequency at constant voltage

$f \downarrow$ at constant V_1, the value of airgap flux $\uparrow$
Due to this a) motor ct increased b) more losse
c) Very low efficiency.

ii) High frequency operation at constant voltage

V_1 constant f increases ϕ decreases. Due to thi
a) No-load speed increases b) T_{max} decreases
c) T_{st} reduces d) I_{st} decreases.

The base speed ω_b is defined as the synchronous speed corresponds to the rated frequency. The synchronous speed at any other frequency is equal to

$$\boxed{\omega_s = \beta\,\omega_b}$$

β = per unit fre

$$\beta = \frac{\omega_s}{\omega_b} = \frac{f}{f_{rated}}$$

$$s = \frac{\beta\,\omega_b - \omega_m}{\ } = 1 - \frac{\omega_m}{\ }$$

Torque eqn. is becomes,

$$T_d = \frac{3 R_r' V_1^2}{S\beta \omega_b \left[\left(R_s + \frac{R_r'}{s}\right)^2 + \left(\beta X_s + \beta X_r'\right)^2 \right]}$$

If R_s is negligible T_d becomes the T_{max} at base speed.

$$T_{mb} = \frac{3V_1^2}{2\omega_b (X_s + X_r')}$$

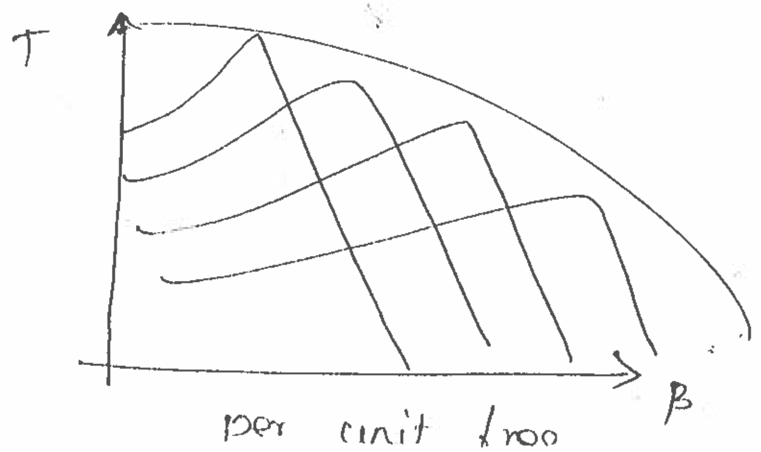
T_{max} at any other frequency

$$T_m = \frac{3}{2\omega_b (X_s + X_r)} \left(\frac{V_1}{\beta}\right)^2$$

$$S_m = \frac{R_r}{\beta (X_s + X_r')} \qquad [R_s \text{ is negligible}]$$

$$\boxed{\frac{T_m}{T_{mb}} = \frac{1}{\beta^2}}$$

* $\beta > 1 \Rightarrow$ IM works at constant terminal vtg, airgap flux is reduced, T is limited.
* $1 < \beta < 1.5$ the relationship b/w T_m & β can be linear
* $\beta < 1 \Rightarrow$ Constant flux, reduced supply volt,



Variable frequency AC motor drives :

The variable frequency ac drives applications are pumps, fans, mill run out tables, blowers, Compressors, conveyors, etc.

The variable frequency is obtained by
i) VSI ii) CSI iii) Cycloconverter

Voltage source inverter fed ac drives :

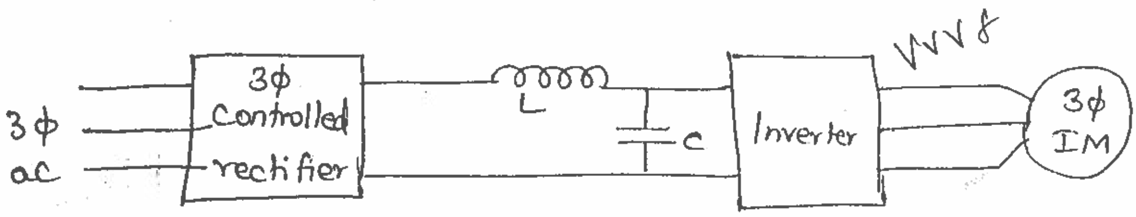


fig (a)

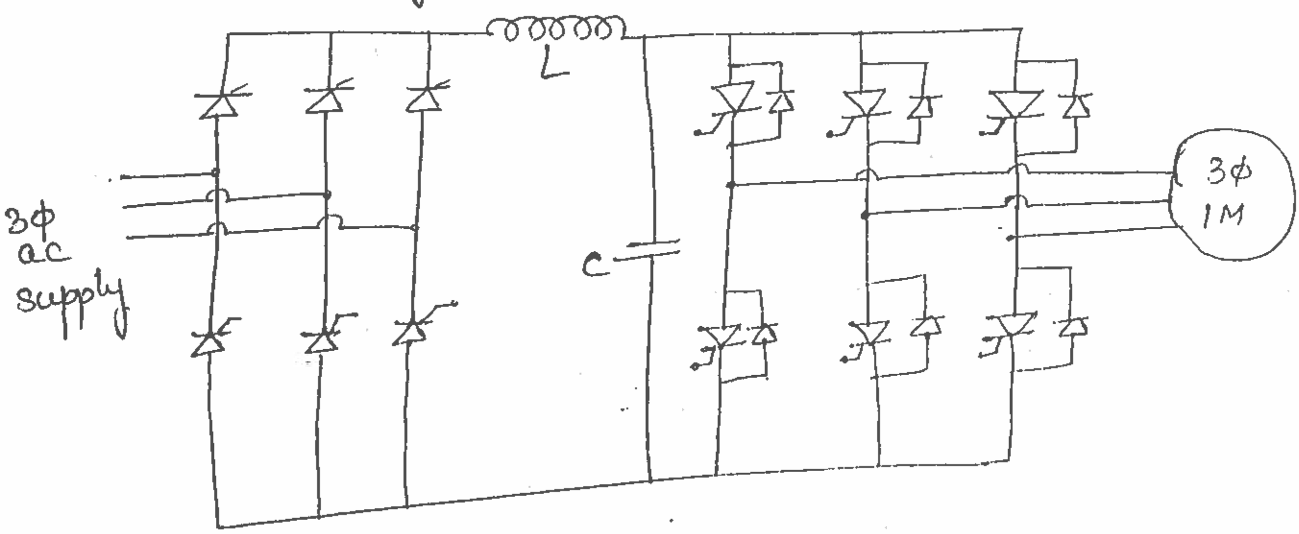


fig (b)

It is the variable voltage variable frequency control. It consists of a 3φ controlled rectifier, filter and inverter. The 3φ controlled rectifier conve

3φ ac supply voltage to variable dc voltage. This voltage is fed to the filter circuit. Here the inductor L acts as the filter. The o/p voltage of the filter is fed to the inverter. The inverter produces a <u>variable voltage</u> and <u>variable frequency</u>. The o/p of the inverter is used to control the i/p of the motor.

The second scheme of speed control of IM as shown in fig

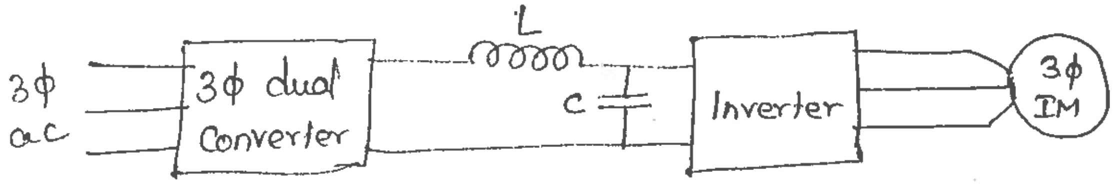
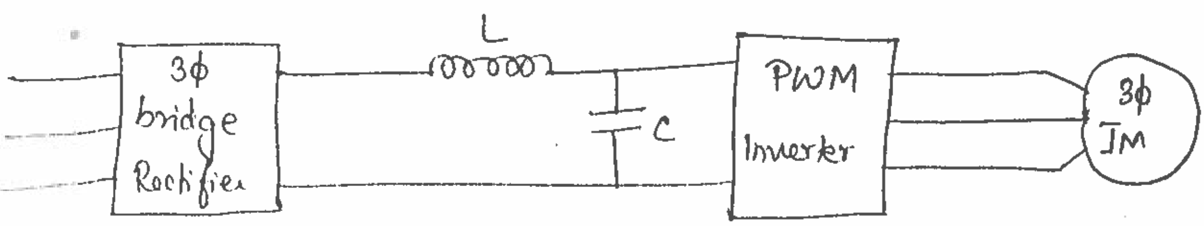


fig (c)

The block diagram consists of dual converter, filter and an inverter. The previous system is not able to regenerate because a reversal of i_o would be required of regeneration is necessary. The phase controlled rectifier is replaced by dual converter. The i/p dc vlg is fed to the inverter and is constant due to the capacit

The inverter output is a variable vlg and variable frequency. The o/p vlg is fed to the inverter.

The third scheme of speed control of IM as shown in fig(



The block diagram consists of 3ϕ bridge rectifier, filter and a PWM. inverter. The diode bridge rectifier converts ac to fixed dc. This constant dc voltage is fed to the PWM inverter. Here, the pulse width modulation technique are applie in the inverter circuit. We can get variable voltage and variable frequency.

The fourth scheme of speed control is shown in fig (e)

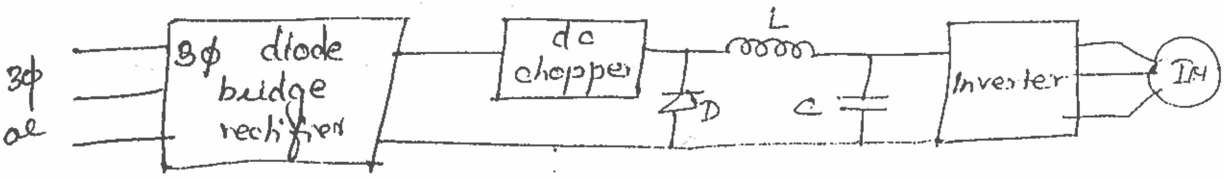


fig (e)

It consists of a 3ϕ bridge rectifier, dc chopper filter and inverter. The diode bridge rectifier converts fixed ac to fixed dc voltage. The ~~fixed~~ dc chopper is used to get variable dc from fixed dc. Due to chopper, the harmonic injection into the ac supply is reduced. This scheme is mainly used for when high frequency o/p is required. Using diode bridge rectifier, the i/p power factor is high.

CSI fed ac drives :

* In VSI the o/p vtg is controlled by the input voltage.
* In CSI the i/p current is kept constant and the o/p current depends upon the nature of the load.
* A large value of inductance connected in series with vtg source, it acts as a constant current source.

The first scheme of CSI fed drive is shown in fig (a).

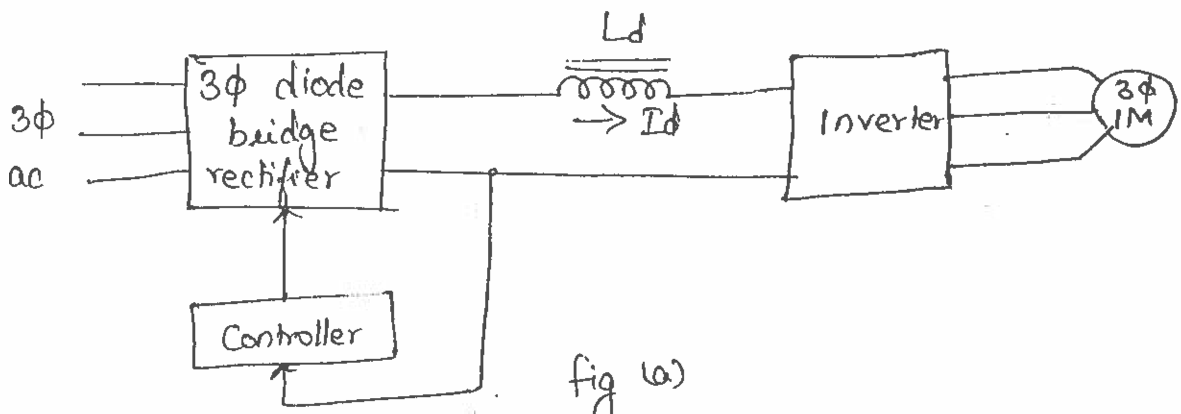


fig (a)

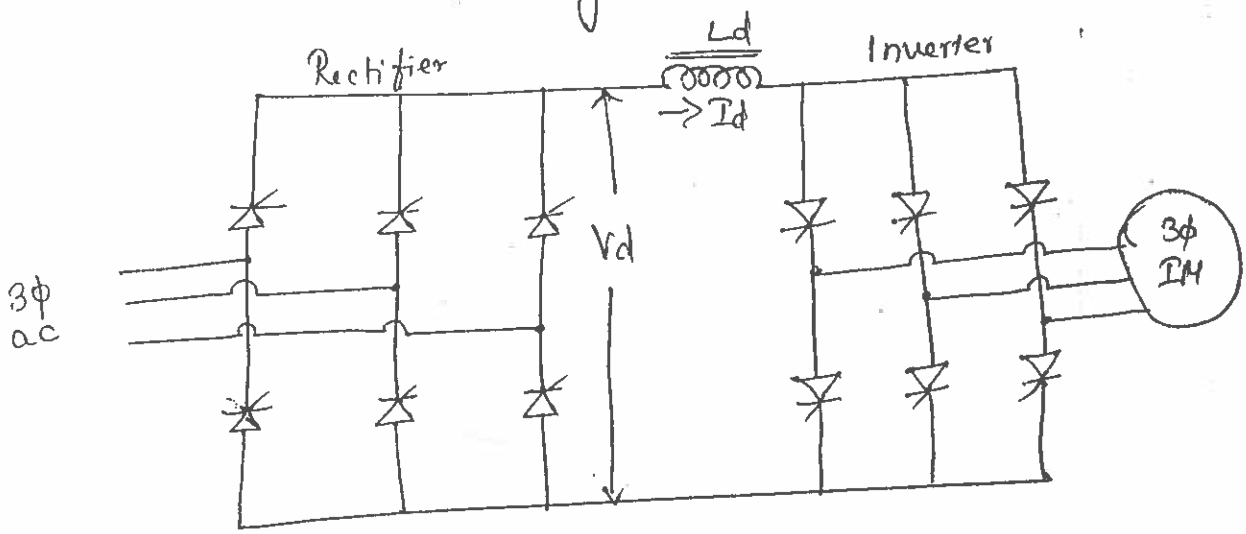


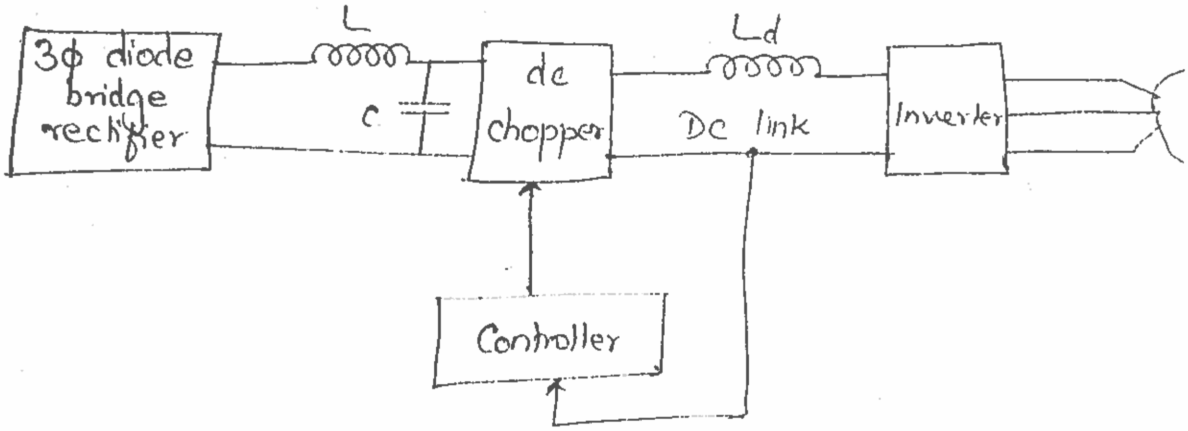
fig (b)

It is a variable voltage and variable frequency Control method. It consists of 3φ rectifier, inductor L and inverter. 3φ ac voltage is converted into variab dc using the 3φ rectifier. The dc voltage is conve into dc current by passing it through a large val of inductor in series with voltage source. The inver frequency is controlled by varying the ~~of~~ triggering of the inverter ckt SCRs. The output of the inverter variable current and variable frequency, which is u to control the speed of the IM. The controller ckt used to vary the firing angle of the controlled rectifi

<u>Adv</u> :- Forced commutation is not required.

<u>Disadv</u> :- Poor PF at low load.

Second scheme of the CSI fed drive as shown in fig



The diagram consists of 3φ diode bridge rectifier, c chopper, inductor Ld and inverter. 3φ diode bridge rectifie is used to convert fixed ac to fixed dc voltage. This o/p vtg is fed to the chopper. This dc chopper convert fixed dc into variable dc voltage. The inductor is used to convert dc voltage to dc current. The constant current is fed to the inverter ckt. The inverter output is variable voltage, variable frequency which is used to control the speed of the motor. The dc chopper o/p vtg is controlled by controller circuit.

Disadv :- * Additional converter is needed.
* Forced commutation of chopper thyristor is reqd.

Adv :- * Power factor is high.

Rotor Side Control :

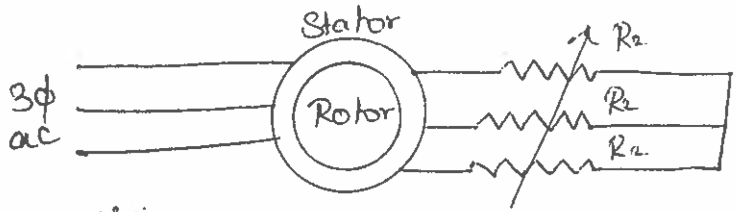
Disadvantages of (SRIM)

1. It is heavier because wound rotor
2. Higher cost
3. High speed limitation
4. Maintenance & Reliability problem due to slip rings.

It is simplest and oldest method, speed can be controlled by mechanically varying rotor ckt rheostat. The main feature of this method is slip power easily electronically controlled for control speed of the motor. For limited range speed control applicable, because the slip power is only a fraction of the total power rating of machine.

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

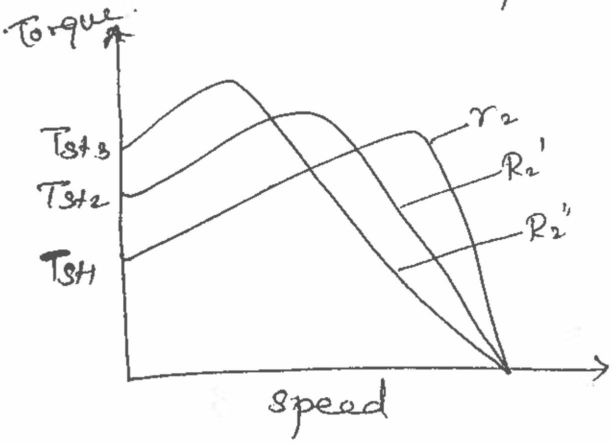
Conventional Rotor Resistance Control



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

$R_2 \rightarrow$ external resistance

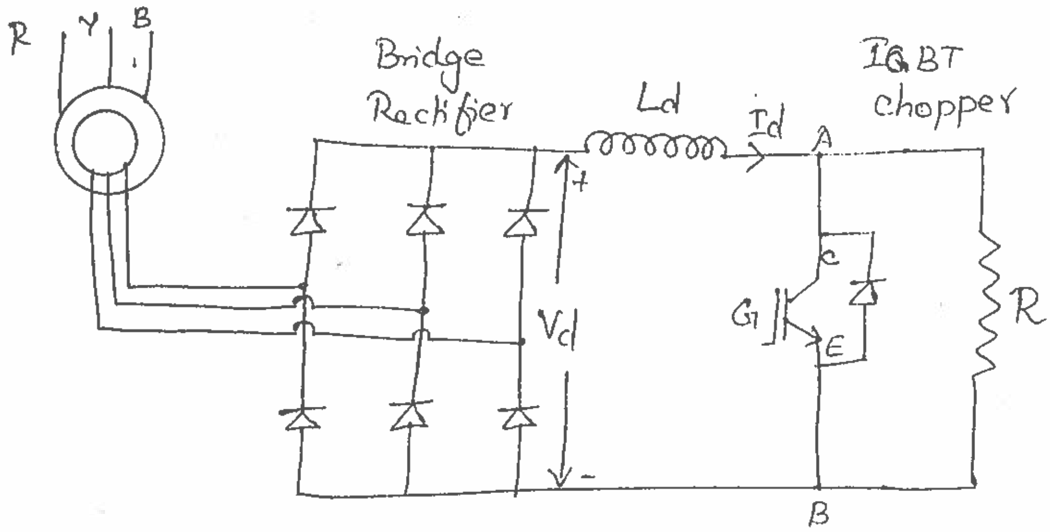
$$T_{max} \propto \frac{E_2^2}{2X_2^2}$$



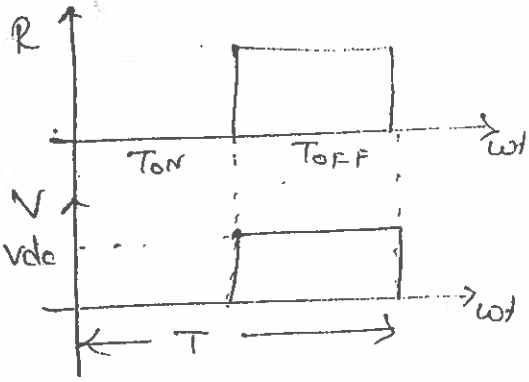
$R_2'' > R_2' > r_2$

By increasing rotor ckt resistance, the T_{max} is consta

Static Rotor Resistance Control :-



* High starting torque at low starting current
* Improved power factor
* Wide range of speed control.



when IGBT is ON

$V_{dc} = V_d = 0$ & $R = 0$

when IGBT is OFF

$V_{dc} = V_d$

The effective external resista

$$R_e = \frac{1}{T}\int_0^T R\,dt$$

$$R_e = \frac{1}{T}\left[\int_0^{T_{ON}} R\,dt + \int_{T_{ON}}^{T} R\,dt\right]$$

$$= \frac{1}{T}\int_{T_{ON}}^{T} R\,dt = \frac{R}{T}\left[T - T_{ON}\right] = R\left[\frac{T}{T} - \frac{T_{ON}}{T}\right]$$

$$\boxed{R_e = R(1-\delta)}$$

Disadv :

1. Slip power is wasted in rotor ckt, hence η reduced
2. Speed changes very widely with load variation.
3. If rotor ckt resistance are not equal unbalanced voltage and current.

Adv :

1. Absence of in-rush starting current.
2. Availability full rated starting torque
3. High line PF
4. Absence of line current harmonics.
5. Smooth and wide range of speed control.

Solid state slip power recovery system :

The power delivered to the rotor across the air gap (P_{ag}) is equal to the mechanical power (P_m) delivered to the load and the rotor copper loss (P_{cu}). Thus

Rotor power = mechanical loss + rotor copper loss

$$P_{ag} = P_m + P_{cu}$$

$$P_{ag} = \omega_s T, \quad P_m = \omega T$$

$$\omega = \omega_s (1-s)$$

$$P_{cu} = s\,\omega_s T$$

$$\boxed{s P_{ag} = \text{Slip power}}$$

$$P_m = (1-s) P_{ag}$$

where T = electromagnetic torque developed by the mo.

ω_s = synchronous angular velocity

In rotor control method, large slip power is dissipated in the resistance and this reduces the efficiency of the motor at low speed. This slip power is recovered to the supply source can be used to supply an additional motor which is mechanically coupled to the main motor. This type drive is known slip power recovery system. It improves the overall efficiency of the system. The speed of SRIM can be controlled both in the sub-synchronous and super-synchronous regions. This is called cascade connection.

Condition for sub synchronous:

Slip power is taken from Rotor and fedback to supply for this condition motor operate in sub-synchronous region.

Rotor (slip power) $\longrightarrow$ main source [E(ext)]

Condition for super synchronous :

The power flows from source to the rotor and mo operates in the super - synchronous region.

Main source → rotor side

Types of slip power recovery system :

1. Kramer System 2. Scherbius system.

These two systems can further be classified into

1. Conventional method
2. Static method.

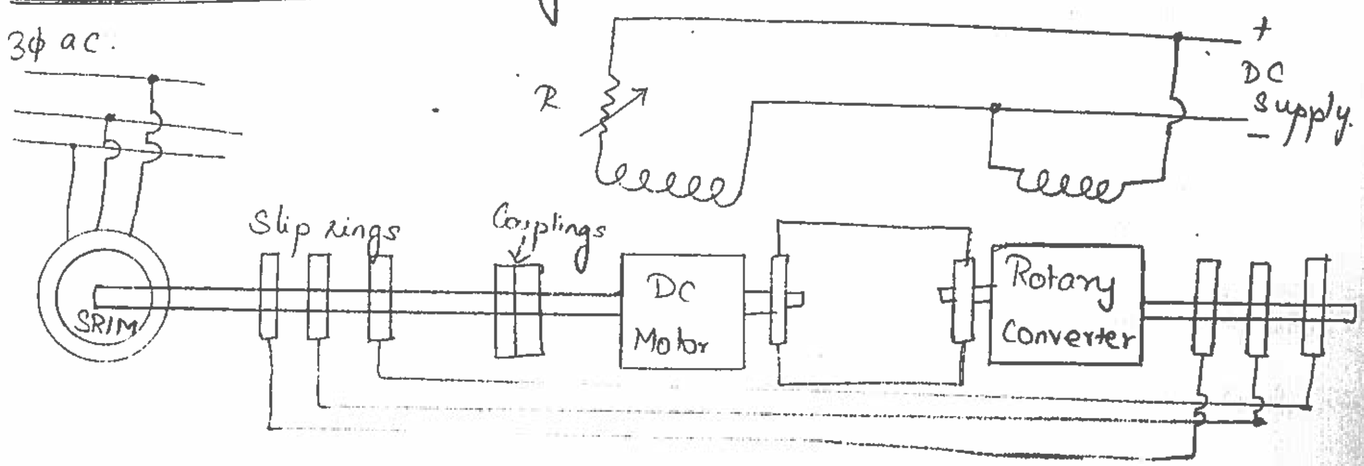
Kramer System :

The kramer system is only applicable for sub - synchronous speed operation. The classification of Kramer system is

a. Conventional kramer system.

b. Static Kramer system.

Conventional Kramer System :



The system consists of 3ϕ rotary converter and motor. The slip power is converted into dc power a rotary converter and fed to the armature of a dc

The slip ring IM is coupled to the shaft of the motor. The slip rings are connected to the rotary co The dc o/p of rotary converter is used to drive a dc The rotary converter and dc motor are excited from the dc bus bars or from an exciter. The speed of SRIM is adjusted by adjusting the speed of dc mot with the help of a field regulator.

This system is also called the electromechanical casca because the slip frequency power is returned as mechanical power to the SRIM shaft by the dc mo

$$P_m = (1-S) P_{in} \quad , \quad P_{in} \rightarrow I/p \text{ power to the ,}$$

The slip power $P_s = S P_{in}$ is added to P_m by converting it to mechanical power by the dc motor. The mechanical power is fed to the SRIM shaft.

Adv :

1. Speed within the working range is possible.
2. If the rotary converter is over excited, it will ta a leading current with compensates for the lagging current drawn by SRIM and hence improves the of the system.

Modified Kramer System :

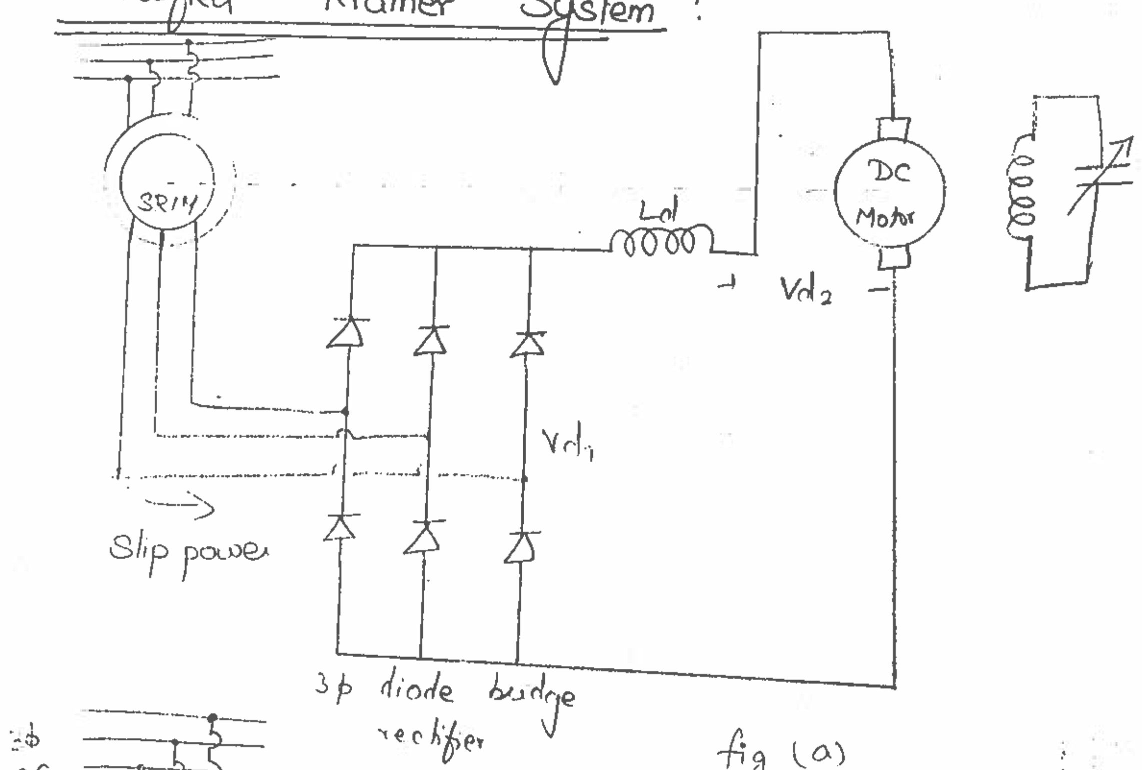


fig (a)

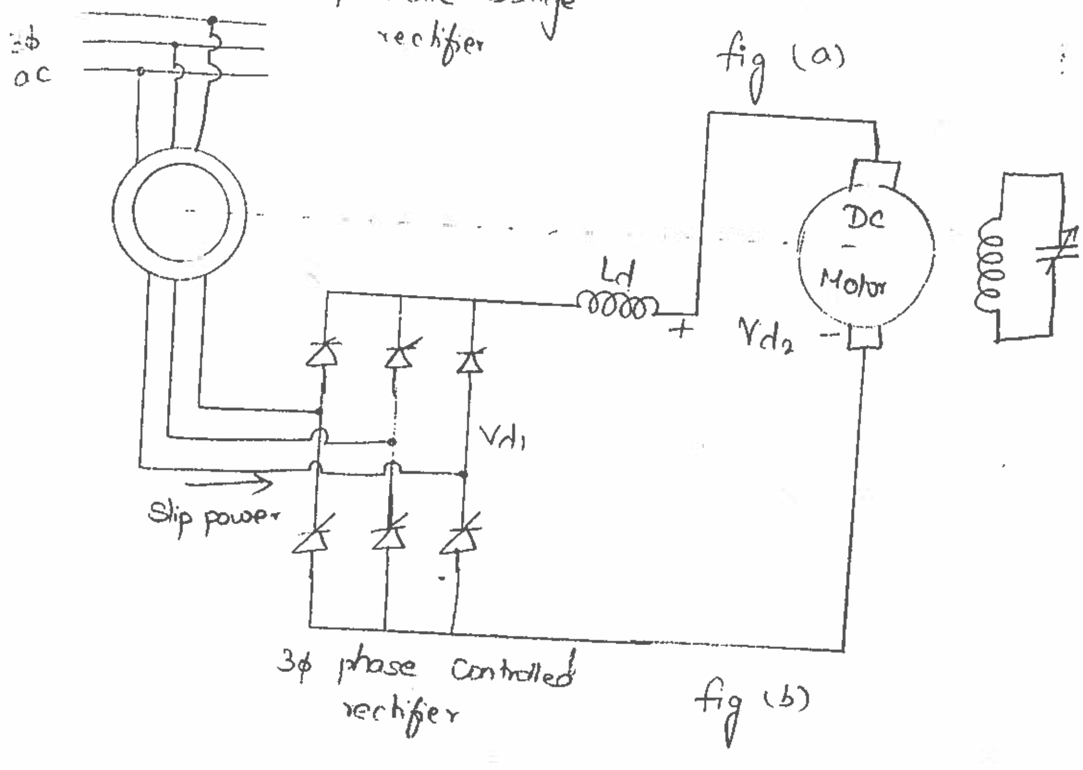


fig (b)

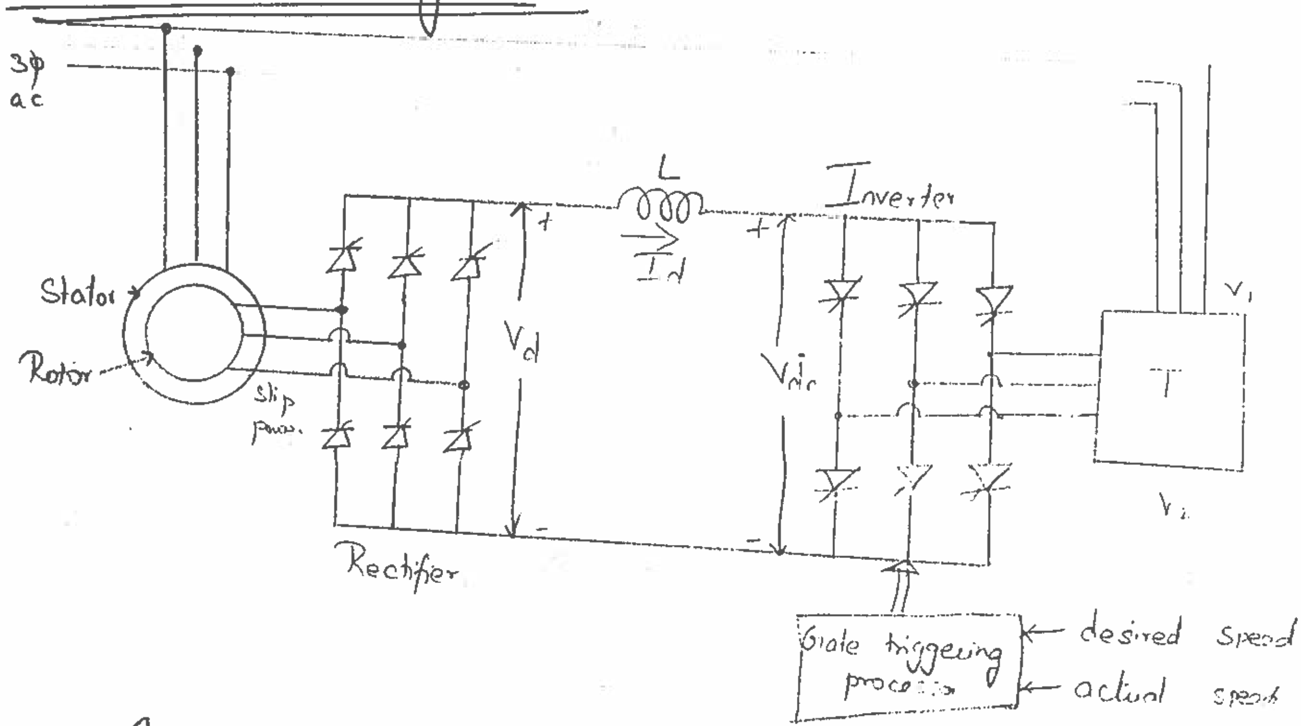
Here, the rotary converter is replaced by a 3φ diode bridge rectifier or 3φ controlled rectifier.

The slip power is converted into dc by a 3φ diode bridge rectifier fig (a). The dc power is fed to the dc motor. The dc motor is mechanically coupled to SRIM. The slip power is converted to mechanical power and fed back to the SRIM shaft. The SRIM speed can be controlled by controllin
the field ...

Speed control range is synchronous speed to arou half of the synchronous speed.

Fig b. Shows the diode bridge rectifier is replaced thyristor bridge rectifier. The SRIM speed can be controlled from zero to around synchronous speed by varying the firing angle of thyristor rectifier.

Static Kramer System :



In rotor resistance control method, the slip power is wasted in the rotor circuit resistance. Instead of wasting slip power in the rotor circuit resistance, it can be converted to 50Hz ac and pumped back to the line. Here, the slip power can flow only in one direction. This type of drive is called static kramer drive.

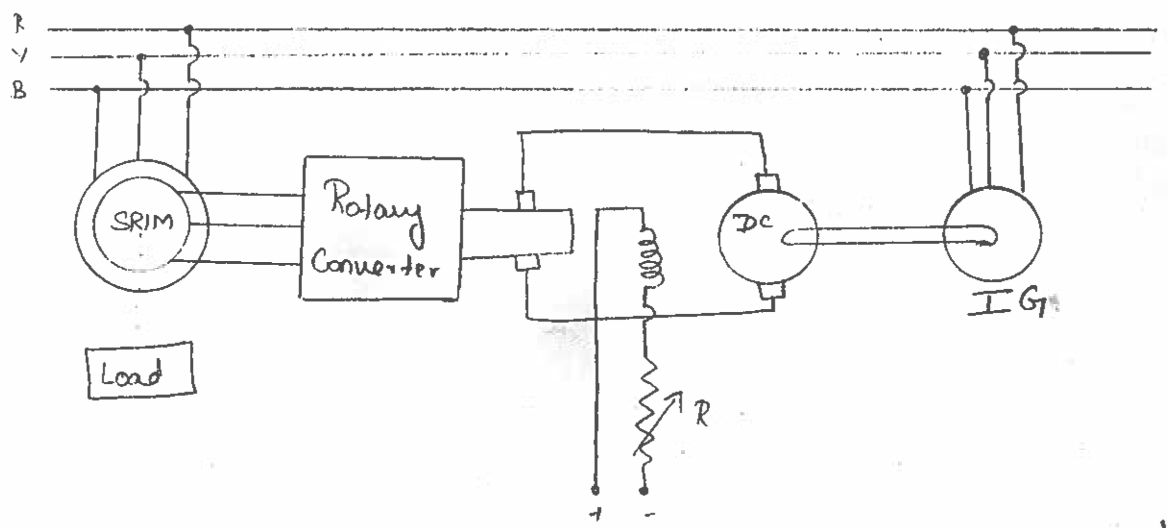
In this method, the slip power is taken from the rotor and it is rectified to dc voltage by 3φ diode bridge rectifiers. Inductor Ld smoothens the ripples in the rectified voltage V_d. This dc power is converted into ac power by using line - commutated inverter. The rectifier and inverter are both line commutated by alternating emfs appearing at the slip rings and supply bus bars respectively. This method is also called as constant - torque drive.

SCHERBIUS SYSTEM:

In the Kramer system the feedback is mechanical and in the scherbius system the return power is electrical. The different types of scherbius systems are

a) Conventional Scherbius drive
b) Static Scherbius drive.

Conventional Scherbius Drive



This method consists of SRIM, rotary converter, dc motor and induction generator. Here the rotary converter converts slip power into dc power and the dc power feed to the dc motor. The dc motor is coupled with IG. The induction generator converts the mechanical power into electrical power and returns it to the supply line.

The SRIM speed can be controlled by varying the field regulator of the dc motor

Static Scherbius System :

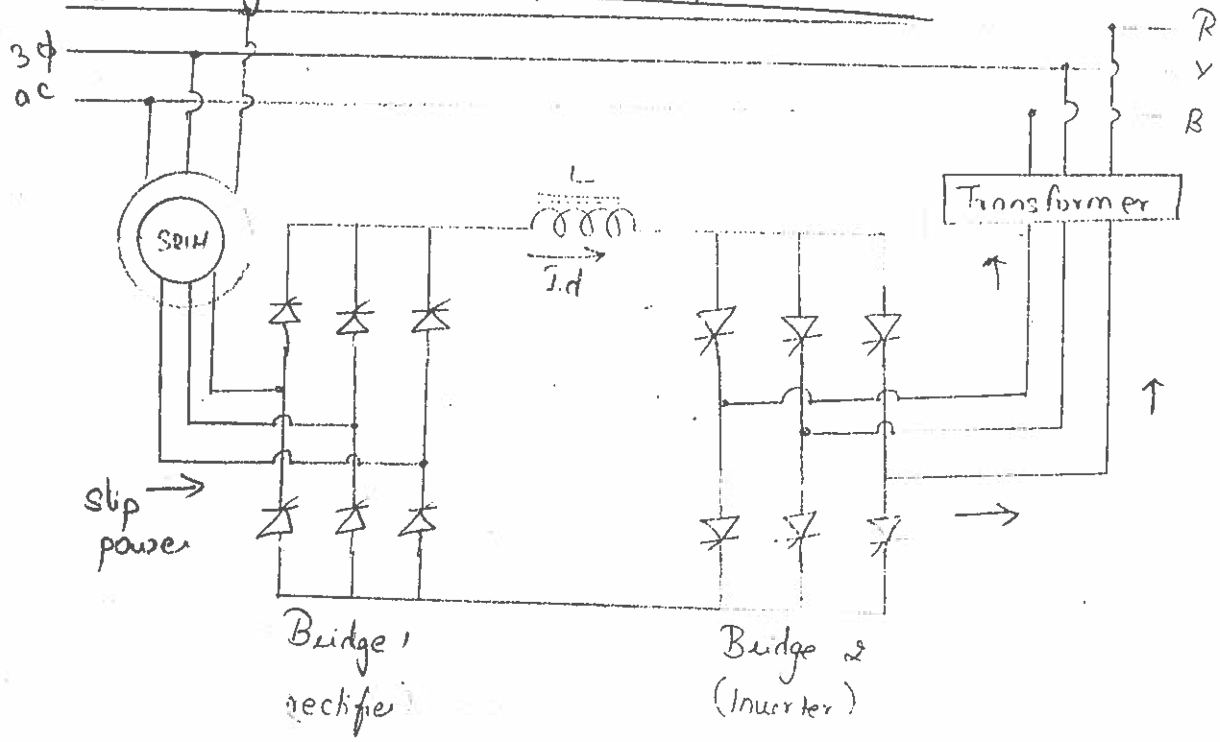
For the speed control of SRIM both below and the synchronous speed, static scherbius drive system is u... This system can again be classified as

1. DC link static scherbius drive
2. Cycloconverter static Scherbius drive.

DC link static Scherbius drive :

This system consists of SRIM, two phase control bridges, smoothening inductor and step up transformer. This system is used for both sub-synchronous and synchronous speed operation.

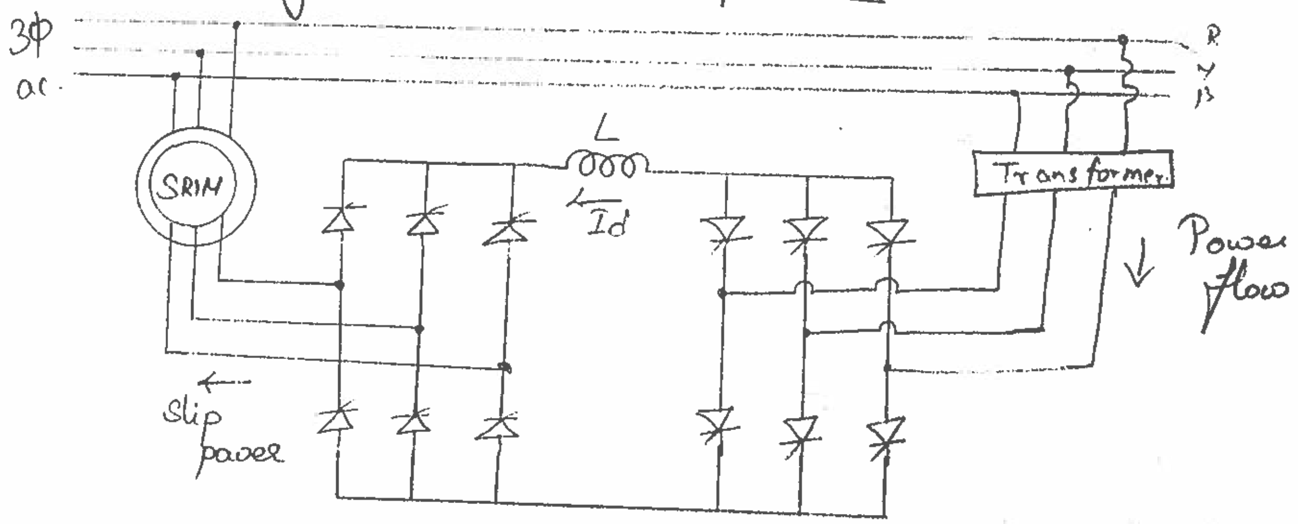
(i) Sub - synchronous speed operation :



In sub-synchronous speed control of SRIM, slip power is removed from the rotor circuit and is pumped back into the ac supply. When the machine is operated at sub-synchronous speed, phase controlled bridge 1 operates in the rectifier mode and bridge 2 operates in the inverter mode. In other words, bridge 1 has firing angle less than 90° whereas bridge 2 has firing angle more than 90°. The slip power flows from rotor circuit to bridge 1, bridge 2, transformer and returned to the supply.

Slip power → rectifier (bridge 1) → inverter (bridge 2) → Transformer → supply

(ii) Super synchronous speed operation:

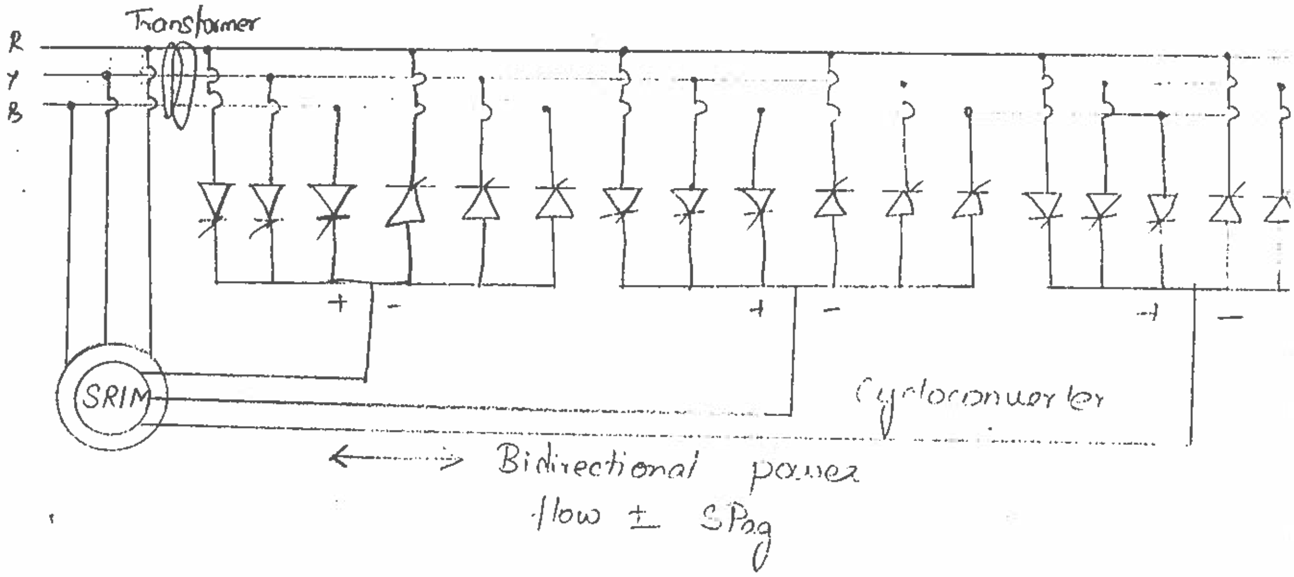


In super-synchronous speed operation, the additional power is fed into the rotor circuit at slip frequency. When the machine is operated at super synchronous speed, phase controlled bridge 2 should operate in rectifier mode and bridge 1 in inverter mode.

Supply → transformer → bridge 2 (rectifier) → bridge 1 (inverter) → rotor circ

CYCLOCONVERTER STATIC SCHERBIUS DRIVE :

The Kramer drive system has only a forward motoring mode of operation. But, this system is applicable for both motoring and regenerating in both subsynchronous and super synchronous ranges of speed.



Here the slip power flow in either direction. The various modes of operation is shown below can be explained as follows assuming motor shaft is constant and the losses in the motor and cyclo are negligible.

Mode 1. Sub-synchronous motoring :

This mode is similar to that of static Kramer system. The stator input or air gap power Pag remains Constant and the slip power sPag, which is proportion to the slip, is returned back to the line through the cycloconverter. Therefore, the line supplies the net mechanical power $P_m = (1-s)P_{ag}$ consumed by the shaft. The slip frequency power in the rotor creates a rotating field in the same direction as in the stator and the rotor speed ω_r corresponds to the difference $(\omega_s - \omega_{sl})$ between these two frequencies. At slip is equal to zero, the cycloconverter supplies dc excitation to the rotor and the machine behave like a standard synchronous motor.

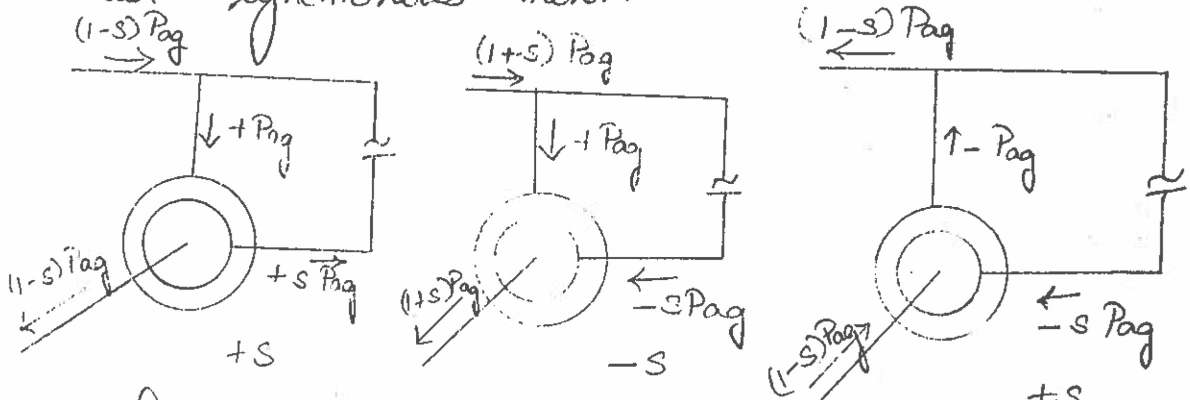


fig (a) fig (b) fig (c)

Mode 2 Super - synchronous mode :

As shown in fig (b), the shaft speed increases beyond the synchronous speed, the slip becomes negative and the slip power is absorbed by the rotor. The slip power sP_{ag} supplements the air gap power P_{ag} for the total mechanical power output $(1+s)P_{ag}$. The line therefore supplies slip power in addition to stator input power. During this condition, the slip voltage is reversed, so that slip frequency - induced rotating magnetic field is opposite to the of the stator.

Mode 3 Sub-Synchronous Regeneration :

As shown in fig (c), the shaft is driven by the l and the mechanical energy is converted into electri energy. With constant negative shaft torque, the mechanical power i/p to the shaft $P_m = (1-s) P_{ag}$ increases with speed and this equals the electrical power fed to the line. In the sub-synchronous s range, the slip s is positive and the air gap po P_{ag} is negative. At synchronous speed, the cycloconv supplies dc excitation current to the rotor circuit a the machine behaves as a synchronous generator. The main application in this is a variable - speed winc generation system.

Mode 4 Super-synchronous regeneration :

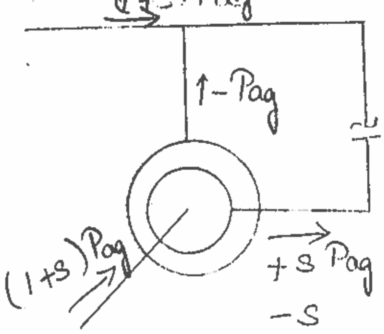


fig (d)

The super-synchronous regene is shown in fig (d). Here, the stator output power remains constant, t the additional mechanical power in is reflected as slip power output. the rotor field rotates in the opposit direction because the cycloconverter p sequence is reversed.

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CHAPTER - 3

VECTOR CONTROL

3.1) INTRODUCTION: -

The various control strategies for the control of the inverter-fed induction motor have provided good steady state but poor dynamic response. From the traces of the dynamic responses, the cause of such poor dynamic response is found to be that their air gap flux linkages deviate from their set values. The deviation is not only in magnitude but also in phase. The variations in the flux linkage have to be controlled by the magnitude and frequency of the stator and rotor phase currents and instantaneous phases.

The oscillations in the air gap flux linkages result in oscillations in electromagnetic torque and, if left unchecked, reflect as speed oscillations. This is undesirable in many high-performance applications. Air gap flux variations result in large excursions of stator currents, requiring large peak converter and inverter ratings to meet the dynamics. An enhancement of peak inverter rating increases cost and reduces the competitive edge of ac drives over dc drives.

Separately-excited dc drives are simpler in control because they independent control flux, which, when maintained consists, contributes to an independent control of torque. This is made possible with separate control of field and armature currents which, in turn, control the field flux and the torque independently. Moreover, the dc motor control requires only the control of the field or armature current magnitudes.

As with the dc drives, independent control of the flux and torque is possible in ac drives. The stator current phasor can be resolved, say, along the rotor flux linkages, and the component along the rotor flux linkages is the field producing current, but this requires the position of the rotor flux linkages at every instant; note that this is dynamic, unlike in the dc machine. If this is available, then the control of ac machines is very similar to that of separately-excited dc machines. The requirements of phase, frequency, and magnitude control of the currents and hence of the flux phasor is made possible by inverter control.

The control is achieved infield co-ordinates (hence the names of this control strategy, *field-oriented control*); sometimes it is known as vector control. Vector control made the ac drives equivalent dc drives in the independent control of flux and torque and superior to them in their dynamic performance.

3.2) DC DRIVE ANALOGY: -

Ideally, a vector control induction motor drive operates like a separately excepted dc motor drive. Fig3.1 shows the separately excited dc motor. In a dc machine, neglecting the armature reaction effect and field saturation, the developed torque is given by.

$$T_e = K_t \Psi_f \Psi_a = K_t' i_a i_f \qquad (3.1)$$

Where i_a = armature current & i_f = field current

The construction of a dc machine is such that the field flux Ψ_f Produced by the current I_f is perpendicular to the armature flux Ψ_a, which is produced by armature current i_a. These space vectors, which are stationary in space, are orthogonal or decoupled in nature.

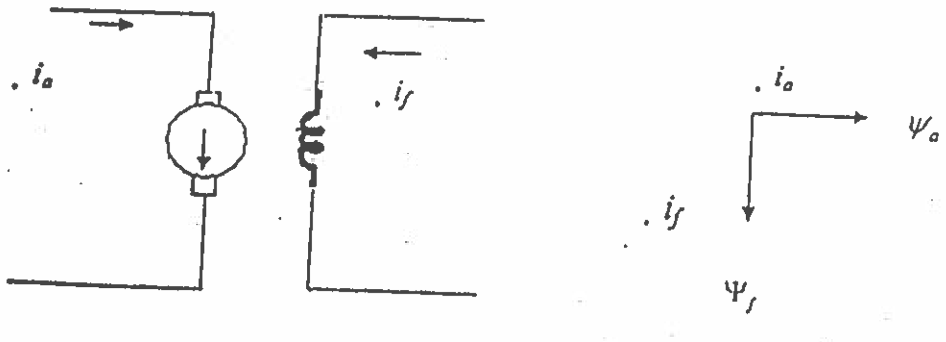

Fig 3.1 Separately excited-motor

This means that when torque is controlled by controlling the current I_a, the flux Ψ_f is not affected and we get the fast transient response and high torque/ ampere ratio with the rated Ψ_f. Because of decoupling, when the field current i_f is controlled, it affect the field flux Ψ_f only, but not the Ψ_a flux. Because of the inherent coupling problem, an induction motor cannot generally give such fast response. [2]

DC machine like performance can also be extended to an induction motor of the machine control is considered in a synchronously rotating reference frame (d^e-q^e), where the sinusoidal variables appear as dc quantities in steady state.

In this figure 3.2 shows the induction motor with the inverter and vector control in the front end is shown with two control current inputs , i_{ds}^* and i_{qs}^*.

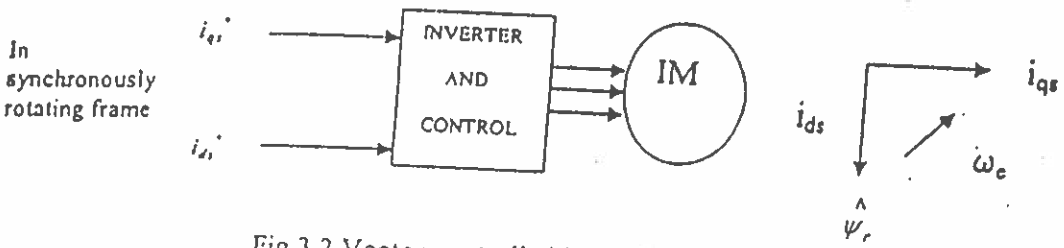

Fig 3.2 Vector controlled induction motor

These current are the direct axis component and quadrature axis component of the stator current, respectively, in a synchronously rotating reference frame. With vector control, i_{ds} is analogous to field current I_f and I_{qs} is analogous to armature current I_a of a dc machine. Therefore, the torque can be expressed as

$$T_e = K_t \hat{\Psi}_r i_{qs}$$

or

$$T_e = K_t' i_{qs} i_{ds} \tag{3.2}$$

Where i_{qs} = torque component & i_{ds} = field component.

$\hat{\Psi}_r$ = absolute $\overline{\psi_r}$ is the peak value of the sinusoidal space vector.

This dc machine like performance is only possible if i_{ds} is oriented (or aligned) in the direction of flux $\hat{\Psi}_r$ and i_{qs} is established perpendicular to it, as shown by the space-vector diagram on the right of figure 3.2. [4] This means that when I_{qs}^* is controlled; it controls the flux only and does not affect the I_{qs} component of current. This vector or field orientation of currents is essential under all operating conditions in a vector-controlled drive. It can be noted when compared to dc machine space vectors, induction machine space vectors rotate synchronously at frequency ω_e, as indicated the figure 3.2. In fact, vector control should assure the correct orientation and equality of command and actual currents.

Equivalent circuit and phasor Diagram: -

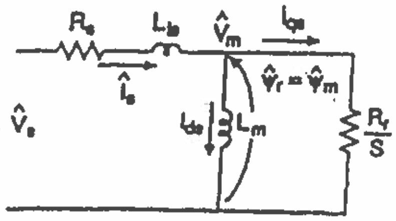

Fig3.3 Complex (qds) equivalent circuit in steady state

Figure 3.3 shows the complex form of d^e-q^e equivalent circuit in steady state condition, where rms values V_s and I_s are replaced by corresponding peak values (Sinusoidal vector variables), as shown [2]. The rotor leakage inductance L_{lr} has been neglected for simplicity, which makes the rotor flux $\hat{\Psi}_r$ the same as the air gap flux $\hat{\Psi}_m$. The stator current $\hat{I}_s$ can be expressed as

$$\hat{I}_s = \sqrt{i_{ds}^{\,2} + i_{qs}^{\,2}} \tag{3.3}$$

Where i_{ds} = magnetizing component of stator current flowing through the inductance L_m,
and i_{qs}= frequency component of stator current flowing in the rotor circuit.

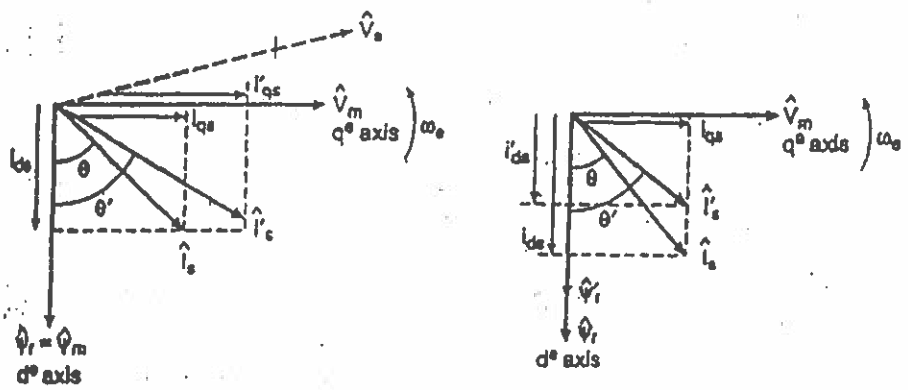

Fig 3.4stady state phasors (in terms of peak values)
(a) Increase of torque component of current, (b) Increase of flux component of current

Figure 3.4 shows the phasor diagrams in d^e- q^e frame with peak values of sinusoids and air gap voltage V_m aligned on the q^e axis [2]. The phase position of the currents and flux as shown in figure, and the corresponding developed torque expression is given by equation 3.2. The terminal voltage V_s is slightly leading because of the stator impedance drop. The in-phase or torque component of current i_{qs} contributes active power across the air gap, whereas the reactive or flux component of current i_{ds} contributes only reactive power. Figure 3.4(a) indicates an increase of the i_{qs} component of the stator current to increase the torque while maintaining the ψr constant, whereas (b) indicates a weakening of the flux by reducing the i_{ds} component.

3.3) PRINCIPLE OF VECTOR CONTROL: -

The fundamentals of vector control implementation can be explained with the help of figure 3.5, where the machine model is represented in a stationary reference frame. Assuming that inverter has units current gain, that is, it generates currents i_a, i_b and i_c as dictated by the corresponding command currents i_a^*, i_b^* and i_c^* from the controller. A machine model with internal conversions is shown on the right. The machine terminal phase currents i_a, i_b and i_c are converted to i_{ds}^s and i_{qs}^s components by 3ϕ-2ϕ transformation. These are converted to synchronously stationary frame.

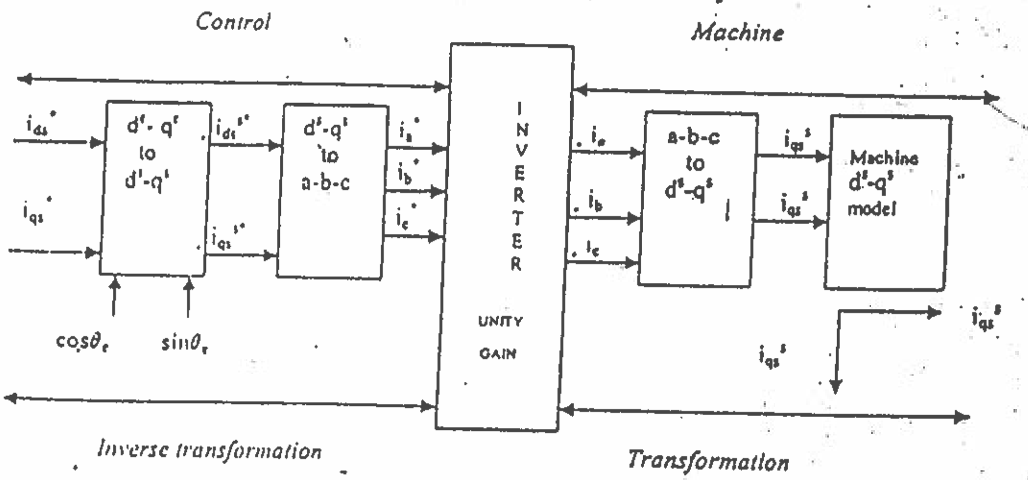

Fig 3.5 Basic block diagram of vector control

Vector control implementation principle with machine d^s-q^s model as shown. The controller makes two stages of inverse transformation, as shown, so that the control currents i_{ds}^* and i_{qs}^* correspond to the machine currents i_{ds} and i_{qs}, respectively. In addition, the unit vector assures correct alignment of i_{ds} current with the flux vector $\bar{\Psi}_r$ and i_{qs} perpendicular to it, as shown. It can be noted that the transformation and inverse transformation including the inverter ideally do not incorporate any dynamics, and therefore, the response to i_{ds} and i_{qs} is instantaneous (neglecting computational and sampling delays).

3.4) TYPES OF VECTOR CONTROL: -

There are essentially two general methods of vector control. They are:

(1) Direct or Feedback method, which was developed by F.Blaschke and

(2) Indirect or Feed forward method, which was developed by K.Hasse.

These methods are differentiated on how the unit vector signals are generated from stator, rotor or air-gap flux signals. In our project we are concentrated on direct method of Vector Control.

BLOCK DIAGRAM OF DIRECT VECTOR CONTROL METHOD:–

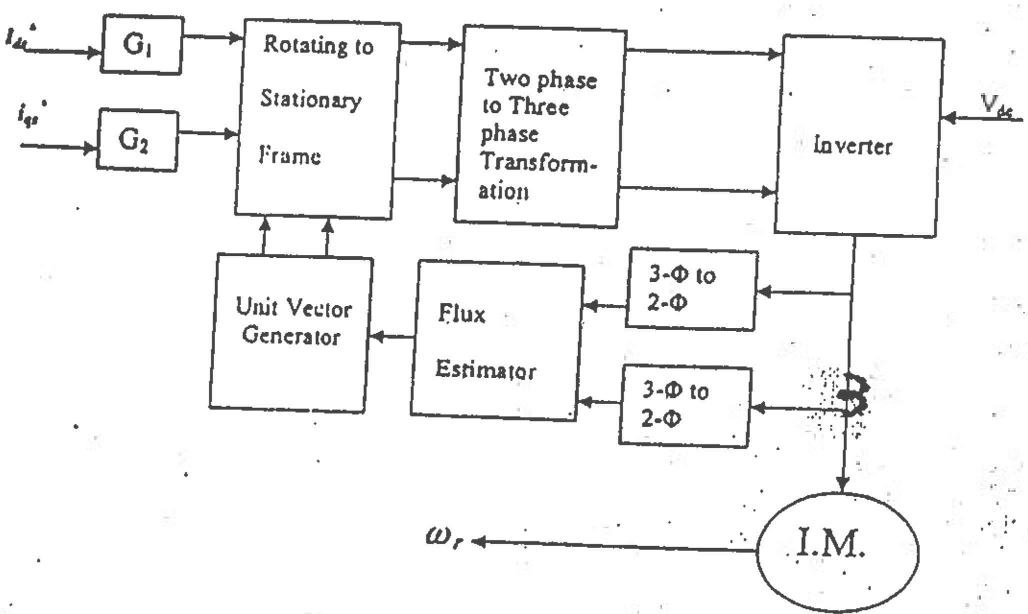

Fig 3.6 Direct Vector Control

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BLOCK DIAGRAM OF INDIRECT VECTOR CONTROL METHOD:-

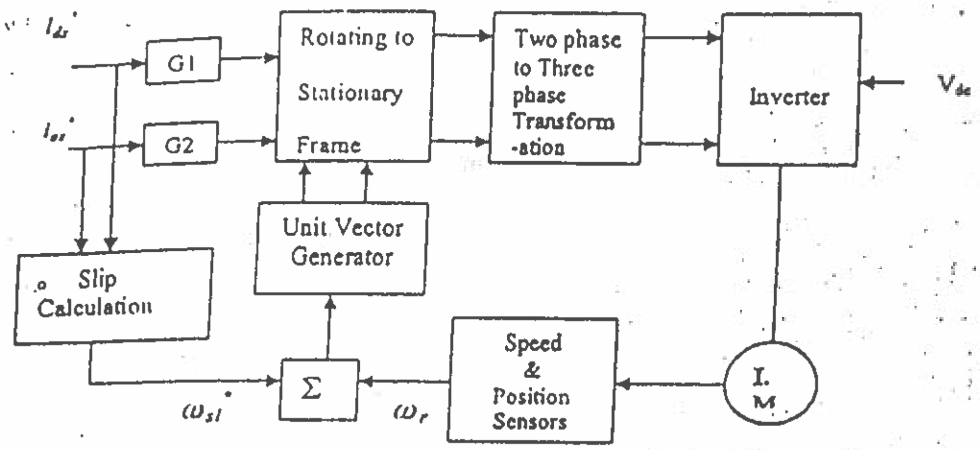

Fig 3.7 Indirect Vector Control.

3.5) DIRECT (or) FEEDBACK VECTOR CONTROL: -

The direct vector control depends on the generation of unit vector signals from the stator or air-gap flux signals. The basic scheme of direct vector control of induction motor is shown in Fig. 3.8

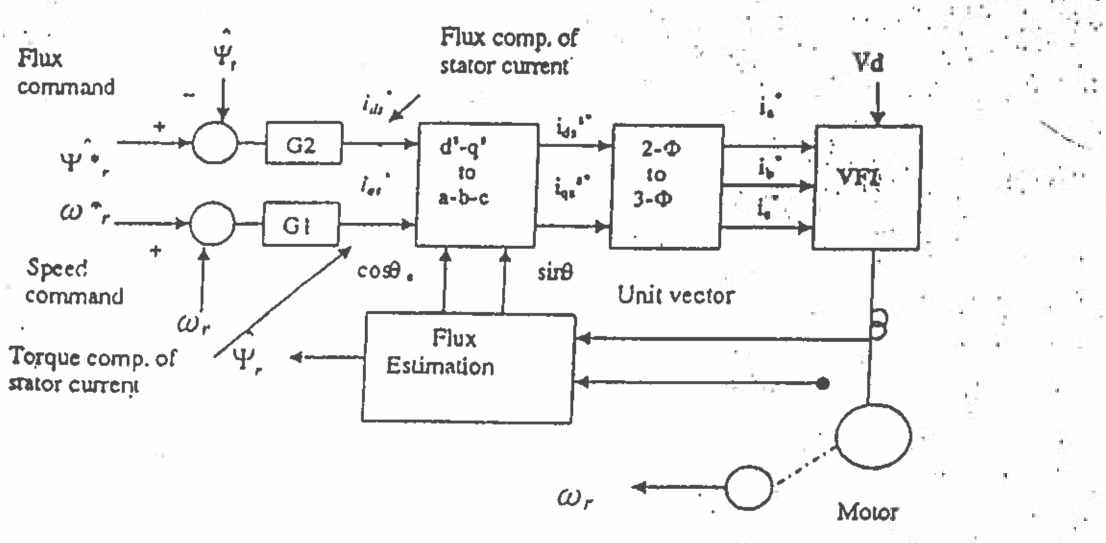

Fig 3.8 Direct vector control block diagram with rotor flux orientation

The basic block diagram of the direct vector control method for a voltage fed inverter drive is shown in fig 3.8. The principle vector control parameters, i_{ds}^* and i_{qs}^*, which are dc values in synchronously rotating frame, are converted to stationary frame with the help of a unit vector ($\cos\theta_e$ and $\sin\theta_e$) generated from flux vector signals Ψ_{dr}^s and Ψ_{qr}^s. The resulting stationary frame signals are then converted to phase current commands for the inverter. The flux signals Ψ_{dr}^s and Ψ_{qr}^s are generated from the machine terminals voltages and currents with the help of the flux estimator. A flux control loop has been added for precision control of flux. The torque component of current i_{qs}^* is generated from the speed control loop through a bipolar limiter. The torque proportional to i_{qs}, can be bipolar. It is negative with negative i_{qs}, and correspondingly, the phase position of i_{qs} becomes negative. An additional torque control loop can be added within the speed loop, if desired. Fig 3.4(b) can be extended to field-weakening mode by programming the flux command as a function of speed so that the inverter remains in PWM mode. Vector control by current regulation is lost if the inverter attains the square-wave mode of operation [2].

The correct alignment of current i_{ds} in the direction of flux $\hat{\Psi}_r$ and current i_{qs} perpendicular to it are crucial in vector control. This alignment, with the help of stationary frame rotor flux vectors Ψ_{dr}^s and Ψ_{qr}^s, is explained in figure 3.9.

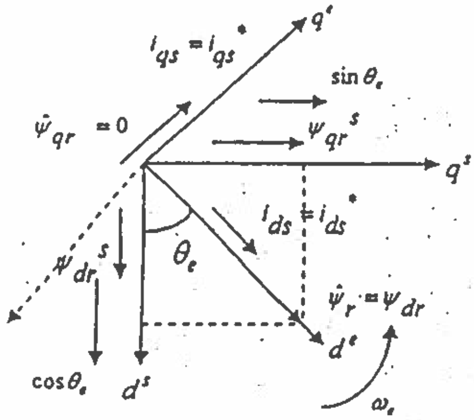

Fig 3.9 d^s-q^s and d^e-q^e phasors showing correct rotor flux orientation

In this figure, the d^e-q^e frame is rotating at synchronous speed with respect to stationary frame d^s-q^s, and at any instant, the angular position of the d^e-axis with respect to the d^s-axis is θ_e. From the figure, we can write the following equations:

$$\Psi_{dr}^{s} = \hat{\Psi}_r \cos\theta_e \tag{3.4}$$

$$\Psi_{qr}^{s} = \hat{\Psi}_r \sin\theta_e \tag{3.5}$$

In other words

$$\cos\theta_e = \frac{\Psi_{dr}^{s}}{\hat{\Psi}_r} \tag{3.6}$$

$$\sin\theta_e = \frac{\Psi_{qr}^{s}}{\hat{\Psi}_r} \tag{3.7}$$

$$\hat{\Psi}_r = \sqrt{\Psi_{dr}^{s^2} + \Psi_{qr}^{s^2}} \tag{3.8}$$

Where vector $\overline{\Psi_r}$ is represented by magnitude $\hat{\Psi}_r$. The unit vector signals ($\cos\theta_e$ and $\sin\theta_e$), when used for vector rotation in fig. (3.8), give a ride of current i_{ds} on the d^e-axis (direction of $\hat{\Psi}_r$) and current i_{qs} on the q^e-axis. At this condition, $\Psi_{qr} = 0$ and $\Psi_{dr} = \hat{\Psi}_r$, as indicated in the figure; and the corresponding torque expression is given by equation (3.2) like a dc machine. When the i_{qs} polarity is reversed by the speed loop, the i_{qs} position also reverses, giving negative torque. The generation of a unit vector signal from feed back flux vectors gives the name "direct vector control" [2].

3.5.1) FLUX VECTOR ESTIMATOR:-

The air-gap signals can be measured directly or estimated from the stator voltage or current signals. The stator flux components can be directly computed from stator quantities. It is necessary to estimate the rotor flux components Ψ_{dr}^{s} and Ψ_{qr}^{s} so that the unit vector and rotor flux can be calculated by equations (3.6)-(3.8). In the low

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In other words

$$\cos\theta_e = \frac{\Psi'^{s}_{dr}}{\Psi'_r} \tag{3.6}$$

$$\sin\theta_e = \frac{\Psi'^{s}_{qr}}{\Psi'_r} \tag{3.7}$$

$$\hat{\Psi}_r = \sqrt{{\Psi_{dr}^{s}}^2 + {\Psi_{qr}^{s}}^2} \tag{3.8}$$

Where vector $\overline{\Psi_r}$ is represented by magnitude $\hat{\Psi}_r$. The unit vector signals ($\cos\theta_e$ and $\sin\theta_e$), when used for vector rotation in fig. (3.8), give a ride of current i_{ds} on the d^e-axis (direction of $\hat{\Psi}_r$) and current i_{qs} on the q^e-axis. At this condition, $\Psi_{qr}=0$ and $\Psi_{dr} = \hat{\Psi}_r$, as indicated in the figure, and the corresponding torque expression is given by equation (3.2) like a dc machine. When the i_{qs} polarity is reversed by the speed loop, the i_{qs} position also reverses, giving negative torque. The generation of a unit vector signal from feed back flux vectors gives the name "direct vector control" [2].

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Inverter Margin Angle Control

In the load commutated synchronous motor drive, the load commutated inverter should be operated with a minimum margin angle, γ, inorder to maximize the motor power factor and efficiency for all loading conditions. This control strategy requires that the inverter advance angle β be continuously adjusted so that an adequate margin angle is allowed after commutation overlap. The inverter margin angle is measured and controlled as shown in the blockdiagram below.

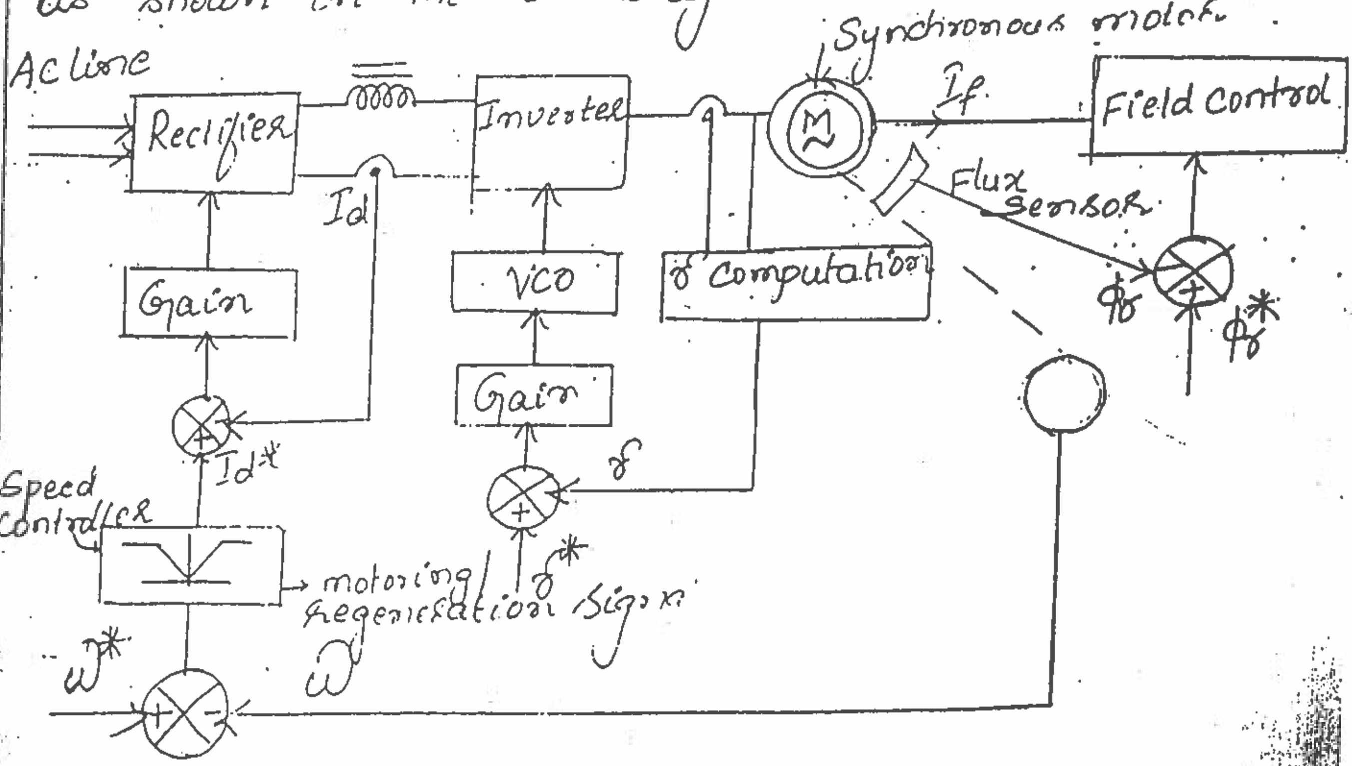


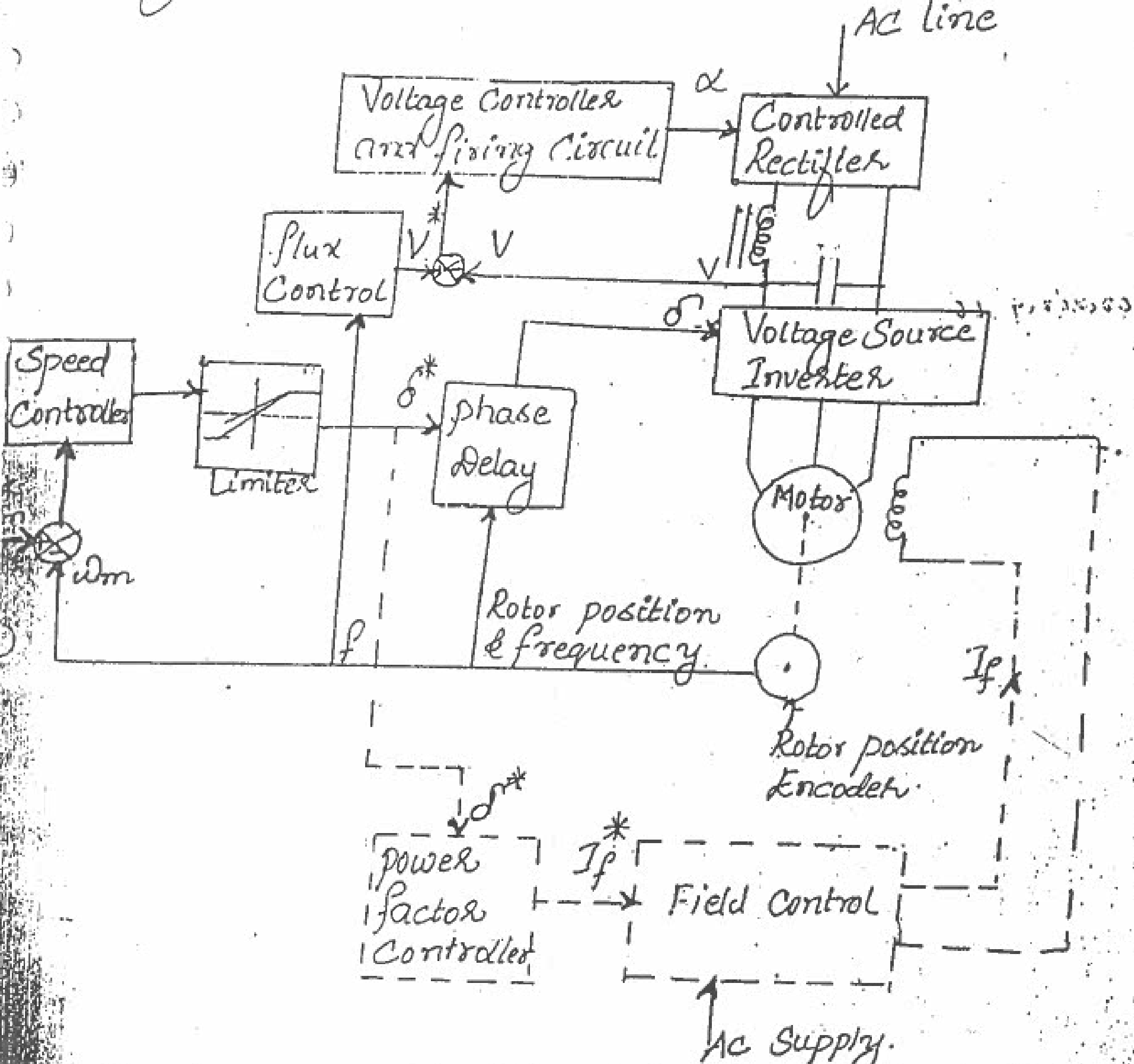
Fig: Synchronous motor drive with closed loop margin angle control of the load commutated inverter.

The stator voltage and currents are sensed and these signals are used to determine the inverter margin angle. The actual value of δ is maintained equal to the command value by phase locked loop control.

Figure shows an outer speed loop and a flux control loop. In constant power region above base speed, the reference flux value is reduced to avoid excessive generated emf at high speeds. The supply side converter delivers a regulated dc current to the load commutated inverter. If the speed error is negative, the rectifier will act as an inverter and inverter acts as a rectifier. The drive enters a regenerative mode, and the angle 'δ' of the machine side converter is increased towards 180° i.e. the firing angle is reduced to zero to give rectifier operation. The supply side converter operates in the inverter mode but continues to regulate the dc link current automatically adjusting its firing angle.

Direct Torque Control (DTC) of Voltage Source Inverter fed Synchronous motors.

Fig. shows a drive employing a synchronous motor fed by a Voltage Source Inverter.



Synchronous motor drive fed from a Voltage Source Inv.

Assume a constant field current If. The encoder ...es the rotor position and frequency Co...

The PM synchronous motors can be classified as (i) surface mounted and (ii) Interior (or buried) and is shown in figure 4.7. The surface mounted PM motor can further be classified as (i) Projecting type in which magnets project from the surface of rotor and (2) inset type in which magnets are inserted into the rotor providing a smooth rotor surface. These rotor are easy to construct and are less expensive, they are less robust compared to interior type rotors and are not suitable for high speed applications. In interior type PM motors, magnets are embedded in the interior of the rotor.

The main drawback of this type of motor is that the power factor cannot be controlled as the field excitation cannot be controlled. The expression for power and torque of projecting type surface magnet machines are same as that of salient pole wound field motors, and those of cylindrical rotor wound field type are applicable to interior and inset type surface magnet machines.

4.2.3 Synchronous reluctance motor

A reluctance motor is nothing but a salient pole motor without a field winding. Hence the torque expression can be obtained from equation (14) by sutistituting E = 0. Thus

$$T = \frac{3V^2}{\omega_{ms}}\left(\frac{X_d - X_q}{2X_d X_q}\right)\sin 2\delta \qquad \dots (15)$$

From the above expression it is clear that the torque is only due to reluctance torque component.

The air gap flux is produced only by the magnestising current drawn from the source, due to the absence of field excitation. Hence, magnetising current drawn is larger which contributes low power factor when compared to other types of synchronous motors.

4.2.4 Hysteresis synchronous motor

The stator of a hysteresis motor can have a single phase (or) 3-phase ac winding. Rotor consists of a single thin walled cylinder made of hard steel. Below the synchronous speed the motor works as a induction motor. Figure 4.8 shows the cross sectional view of the rotor. The current flowing the hard steel rotor produces hysteresis

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and eddy current losses. As the hysteresis loss is proportional to frequency and eddy current loss is proportional to square of the frequency, the equivalent resistance decreases with frequency and has high value at standstill condition and decreases as the rotor speed increases. As a result, the motor has low starting current and develops constant torque at subsynchronous speed.

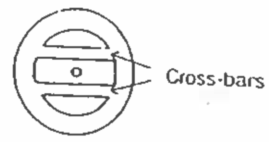


Figure 4.8: Rotor of a hysteresis synchronous rotor

At synchronous speed, the machine operates similar to reluctance motor. The poles are induced along the lines of cross bars. The poles uses formed lock into synchronisation with rotating stator field.

When a stationary motor is connected to the source, it accelerates fast and smoothly ~~as an induction motor and when it~~ reaches near synchronous speed it smoothly pull into step, without any hunting oscillations.

As the synchronous speed is reached, the eddy current and hysteresis losses reduce to zero, as the voltages are not induced in the rotor.

As the rotor has smooth non-salient construction, its operation is smooth and quiet. Small rating hystereris motors are extensively used in tape recorders, fans and high inertia applications.

4.3 Synchronous Motor Variable Speed Drives

Variable frequency control

We know that the synchronous speed is directly proportional to frequency. Similar to induction motors constant flux operation below base speed is achieved by operating the synchronous motor with constant (V/f) ratio. Once the rated voltage is reached at base speed, the machine is operated at rated terminal voltage and variable frequency for higher speeds. The pull out torque is constant for constant flux operation while it is found to decrease with the increase in frequecny for higher speed.

Unlike an induction machine, the synchronous motor either run at synchronous speed (or) it will not run at all. Hence the variable frequency control may employ any of the following two modes (i) True synchronous mode (or) separate controlled mode and (ii) Self-controlled mode.

4.3.1 Separate controlled mode

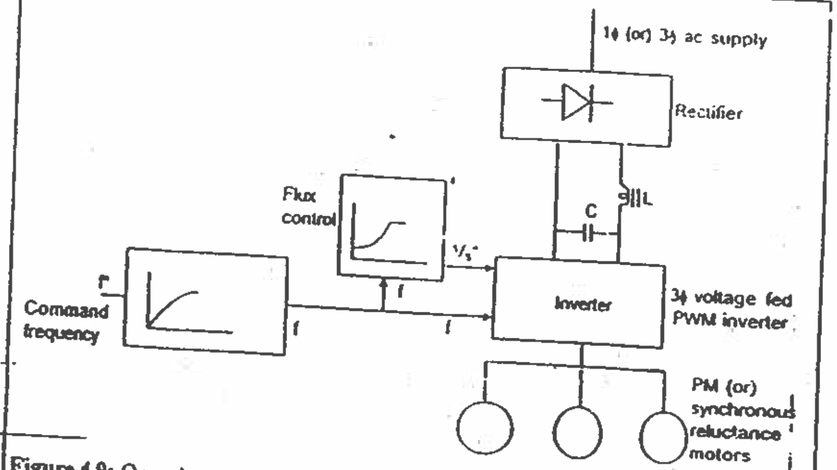


Figure 4.9: Open loop voltage/Hz speed control of multiple PM synchronous motor

In true synchronous mode, is a open loop mode in which the stator supply frequency is controlled from an independent oscillator. Here the frequency is gradually changed from its initial to the desired value is so that the difference between synchronous and rotor speed is always small. This is done so that the rotor always keep track of the changes in synchronous speed. This method is best suited for multiple synchronous reluctance (or) PM machine drives, where close speed tracking is essential among number of machines for application such as fiber spinning mills. When the desired synchronous speed (or frequency) is reached, the rotor pulls into step, after hunting oscillations. This method can also be used for smooth starting and regenerative braking. An example for true synchronous mode is the open loop(V/f) speed control shown in figure 4.9.

Here all the machines are connected in parallel to the same inverter and they move in response to the command frequency f* at the input. The frequency command

f* after passing through the delay circuit is applied to the voltage source inverter (or) a voltage fed PWM inverter. This is done so that the rotor speed is able to track the changes in frequency. A flux control block is used which changes the stator voltage with frequency so as to maintain constant flux for speed below base speed and constant terminal voltage for speed above base speed.

The front end of the voltage fed PWM inverter is supplied from utility line through a diode rectifier and LC filter. The machine can be built with damper winding to prevent oscillations.

4.3.2 Self - Controlled mode

In self-controlled mode, the supply frequency is changed so that the synchronous speed is same as that of the rotor speed. Hence, rotor cannot pull-out of slip and hunting oscillations are eliminated. For such a mode of operation the motor does not require a damper winding.

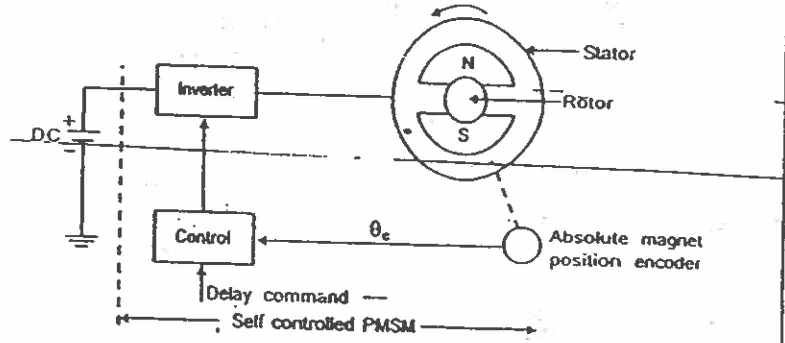


Figure 4.10: Self controlled synchronous motor

Figure 4.10 illustrates a synchronous permanent magnet machine with self control. The stator winding of the machine is fed by an inverter that generates a variable frequency variable voltage sinusoidal supply. Unlike, separate control mode where the controlling of the inverter frequency is from an independent oscillator, here the frequency and phase of the output wave are controlled by an absolute position sensor mounted on machine shaft, giving it self-control characteristics. Here the pulse train from position sensor may be delayed by the external command as shown in the figure 4.10.

Commutatorless

In this kind of control the machine behaviour is decided by the torque angle and voltage/current. Such a machine can be looked upon as a dc motor having its commutator replaced by a converter connected to stator. The self controlled motor run has properties of a dc motor both under steady state and dynamic conditions and therefore, is called commutator less motor (CLM). These machines have better stability behaviour.

Alternatively, the firing pulses for the inverters can also be obtained from the phase position of stator voltages in which case the rotor position sensor can be dispensed with. When synchronous motor are over excited they can supply the reactive power required for commutation thyristors. In such a case the synchronous machine can supply with inverter works similar to the line commutated inverter where the firing signals are synchronised with line voltages. Here, the firing signals are synchronised with the machine voltages then these voltages can be used both for control as well as for commutation. Hence, the frequency of the inverter will be same as that of the machine voltages. This type of inverters are called load commutated inverter (LCI). Hence the commutation has simple configurations due to the absence of diodes, capacitors and auxiliary thyristors. But then this natural commutation its not possible at low speeds upto 10% of base speed as the machine voltages are insufficient to provide satisfactory commutation. At that line some forced commutation circuits must be employed.

4.4 Self Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

Figure (4.11) shows self controlled synchronous motor drive employing a load commutated thyristor inverter. Wound field synchronous motor is used for large power drives. Permanent magnet synchronous motor is used for medium power drives. This drive consists of two converters. i.e., source side converter and load side converter. The source side converter is a 3 phase 6 pulse line commutated fully controlled rectifier. When the firing angle range $0 \le \alpha_s \le 90°$, it acts as a line commutated fully controlled rectifer. During this mode, output voltage V_{ds} and output current I_{ds} is positive. When the firing angle range is $90° \le \alpha_s \le 180°$, it acts as an line commutated inverter. During this mode, output voltage V_{ds} is negative and output current I_{ds} is positive.

When synchronous motor operates at a leading power factor, thyristors of the load side 3ϕ converter can be commutated (turn off) by the motor induced voltages

in the same way, as thyristors of a 3ϕ line commutated converter are commutated by supply voltages. Load commutation is defined as commutation of thyristors by induced voltages of load (here load is synchronous motor).

Triggering angle is measured by comparison of induced voltages in the same way as by the comparision of supply voltages in a line commutated converter.

Load side converter operates as a rectifier when the firing angle range is $0 \le \alpha_\ell \le 90°$. It gives positive $V_{d\ell}$ and I_d.

When the firing angle range is $90° \le \alpha_\ell \le 180°$, it gives negative $V_{d\ell}$ and positive I_d.

For $0 \le \alpha_s \le 90°$, $90 \le \alpha_\ell \le 180°$ and with $V_{ds} > V_{d\ell}$, the source side converter works as a line commutated rectifer and load side converter, causing power flow from ac source to the motor, thus giving motoring operation. When firing angles are changed such that $90° \le \alpha_s \le 180°$ and $0° \le \alpha_\ell \le 90°$, the load side converter operates as a rectifier and source side converter operates as an inverter. In this condition, the power flow reverses and machine operates in regenerative braking. The magnitude of torque value depends on $(V_{ds} - V_{d\ell})$. Synchronous motor speed can be changed by control of line side converter firing angles.

When working as an inverter, the firing angle has to be less than 180° to take care of commutation overlap and turn off of thyristors. The commutation lead angle for load side converter is

$$\beta_\ell = 180° - \alpha_\ell$$

If commutation overlap is neglected, the input ac current of the converter will lag behind input ac voltage by angle α_ℓ. Here synchronous motor input current has an opposite phase to converter input current, the motor current will lead its terminal voltage by a commutation lead angle β_ℓ. Therefore, the synchronous motor operates at a leading power factor. The commutation lead angle is low value, due to this higher the motor power factor and lower the inverter rating.

In a simple control scheme, the drive is operated at a constant value of commutation lead angle $\beta_{\ell c}$ for the load side converter working a line commutated inverter and $\beta_\ell = 180°$ or $\alpha_\ell = 0°$ when working as a rectifer. When good power factor is required to reduce converter rating, the load side converter when working as a line commutated inverter is operated with constant margine angle control. If commutation overlap of the thyristor under commutation is subjected to reverse bias after current through it has fallen to zero is given by

$$\gamma = \beta - u$$

For successful commutation (turn - off) of thyristor

$$\gamma = \omega t_q$$

where t_q = turn off time of thyristor

ω = frequency of motor voltage in rad / sec.

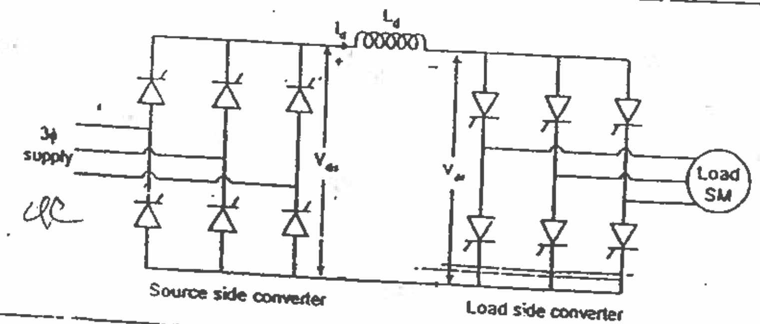


Figure 4.11

4.5 Constant Marginal Angle Control

The operation of the inverter at the minimum safe value of the margin angle gives the highest power factor and the maximum torque per ampere of the armature current, thus allowing the most efficient use of both the inverter and motor.

Figure (4.12) shows the constant margine angle control for a wound field motor drive employing a rotor position encoder. This drive has an outer speed loop and an inner current loop. The rotor position can be sensed by using rotor position encoder. It gives the actual value of speed ω_m. This signal is fed to the comparator. This comparator compares ω_m and ω_m^* (ref value). The output of the comparator is fed to the speed controller and current limiter. It gives the reference current value I_d^*. I_d is the dc link current. It is sensed by current sensor and fed to the comparator. The comparator compares I_d and I_d^*. The output of the comparator is fed to the current controller. It generates the trigger pulses.

It is fed to the controlled rectifer circuit. In addition, it has an arrangement to produce constant flux operation and constant margin angle control.

From the value of dc link current command I_d^*, I_s and 0.5 u are produced by blocks (1)&(2) respectively. The signal ϕ is generated from γ_{min} and 0.5u in adder (3). In block (4) I_f^* is calculated from the known values of I_s, ϕ and I_m. Note that the magnetizing current I_m is held constant at its rated value I_m to keep the flux constant.

I_f^* sets reference for the closed loop control of the field current I_F. Block (5) calculates δ'^* from known, values of ϕ and I_f^*.

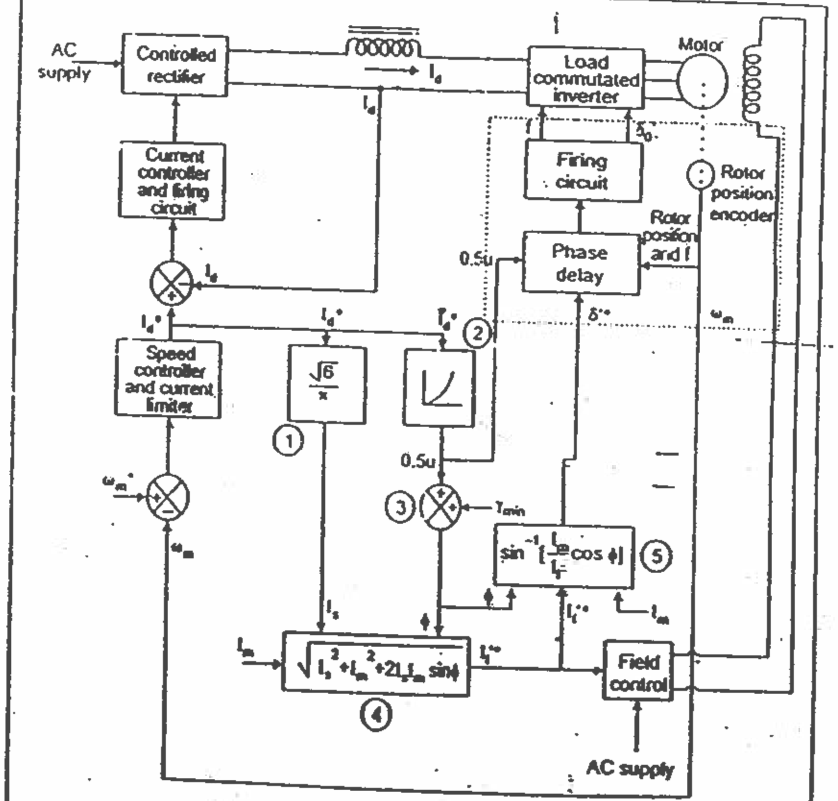


Figure 4.12

The phase delay circuit suitably shifts the pulses produced by the encoder to produce the desired value of δ_r. This signal is fed to the load commutated inverter.

The load commutated inverter drives are used in medium power, high - power and very high power drives, and high speed drives such as compressors, extructers, induced and forced draft fans, blowers, conveyers, aircraft test facilities, steel rolling mills, large ship propulsion, main line traction, flywheel energy storage and so on.

This drive also used for the starting of large synchronous machines in gas turbine and pumped storage plants

High power drives employ rectifiers with higher pulse numbers, to reduce torque pulsations. The converter voltage ratings are also high so that efficient high voltage motors can be employed.

4.6 Voltage Source Inverter (VSI) fed Synchronous Motor

Now a days more attention is being paid towards understanding the behaviour of the synchronous motor fed from a VSI

These drives as said earlier can be developed to have i) Self control mode using a rotor position sensor (or) from phase position of stator voltage.

ii) Separate control mode, where the speed of the motor is determined by the external frequency from a crystal oscillator. This is the open loop control mode.

As discussed earlier, when the motor is self controlled it behaviour in commutator less motor mode (CLM) and has better stability characteristics (both steady state and dynamic). While it is separate control, the motor has instability problems and hunting and behaviour similar to a conventional synchronous motor. A normal VSI with 180° conduction of thyristors requires forced commutation and load commutation is not possible.

Three combinations are possible to provide a variable voltage variable frequency supply to synchronous motor fed from VSI

a) Square wave inverters

b) PWM inverters

c) Chopper with square ware inverters

In all the cases the synchronous motor can be operated, either in separate (or) self controlled mode. All the above schemes are depicted in the figure 4.13 (a), (b), (c) and (d).

(a) Square wave inverters

Here the dc link voltage is variable i e the voltage control is obtained to the inverter using phase controlled rectifier figure 4.13 (a) and (c). The disadvantage of this method is that the commutation is difficult at very low speeds. Hence is applicable since for medium to high speed application. Since the output voltage is a square wave, the inverter is called variable voltage inverter (or) square wave inverter.

(b) PWM inverter

The second method is to have voltage control within the inverter itself using the principles of PWM figure 4.13 (b) and (d). Here the dc link voltage is constant. Here diode rectifier is used on the line side. It doesn't have difficulties in commutation at low speeds. It has wide range of speed applications (even till zero speeds).

(c) Chopper with square wave inverter

The thrid method is to include a dc chopper in between the diode rectifier and the inverter figure 4.14. It has many advantages though it seem to the complex circuitry. Here 3 simple converters are used and is possible to reduce the link inductance by having synchronous control of the chopper.

The output voltage of the inverter is non-sinusoidal, hence the behaviour of the machine will be different from its conventional methods. We must know the steady state performance to determine the effects of non sinusoidal wave froms on torque developed and machine losses. When the synchronous motor is fed from square wave inverter the stator current has sharp peaks and is rich in harmonic content. They also cause pulsating torque, which are completely objectionable especially at low speeds. There will be additional heating and the performance is reduced.

When a PWM inverter is used there hannonic effects are reduced. The stator current are less peaky and have reduced harmonic current and hence additional losses due to harmonic and consequent motor heating and torque pulsations are decreased.

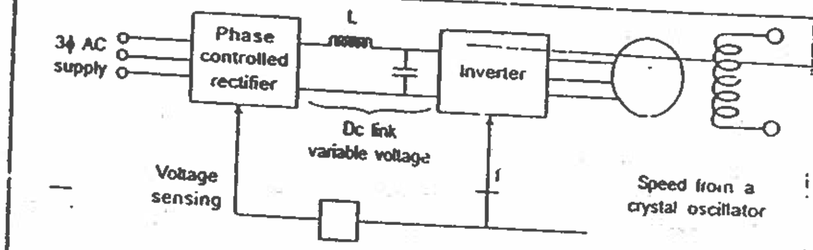
Braking VSI fed synchronous motor must be known. In the square wave inverter, phase controlled rectifier is used in the line side so dynamic braking can be employed. For regenerative braking we have to provide additional phase controlled rectifier on the line side. When PWM inverter is used two cases may arise. The inverter can be either fed from a constent dc source (or) from diode rectifier. In former case regenerative braking is straight forward, where as for latter, a additional phase controlled converter

17\. is required on the line side.

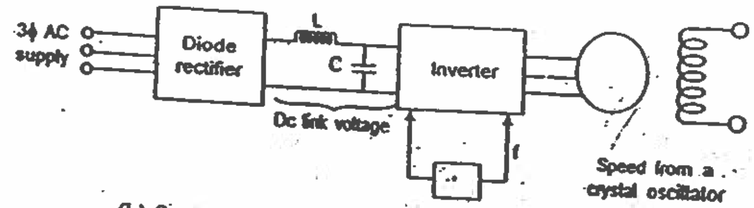
The power factor of the system has to be paid attention. In case of square wave inverter due to the presence of phase controlled recitifier on the line side the power factor is low. While in the PWM inverter since the diode rectifier is present on the line side the line p.f improves to unity. In both the cases the p.f can be changed by inproving the field control. In order to reduce the size of the inverter and also to reduce the losses in the inverter it is preferable to operate the motor at unity power factor.

Generally a VSI fed synchronous motor drive has

- Reasonable efficiency.
- Conveter cost is high.
- Multi motor operation is possible.
- Open loop (separate) control may pose stability problems at low speeds. CLM mode is very stable.
- PWM drive has better dynamic response than square wave drive.
- Find application as general purpose drive for low and medium powers.

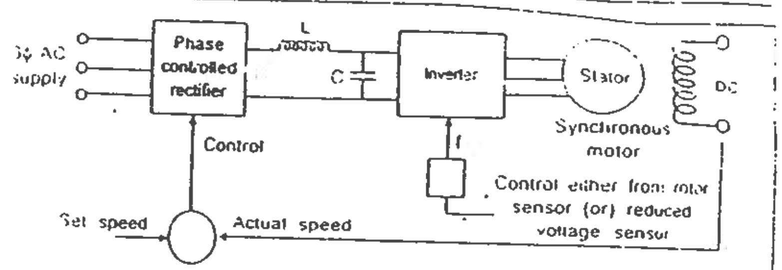


(a) Separate control of SM fed from square wave inverter

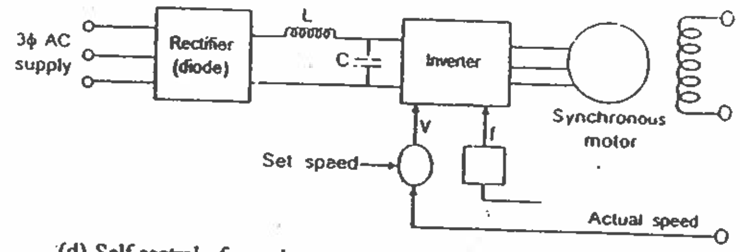


(b) Separate control of SM fed from PWM inverter

Figure 4.13



(c) Self control of synchronous motor fed from square wave inverter



(d) Self control of synchronous motor fed from a PWM inverter

Figure 4.13

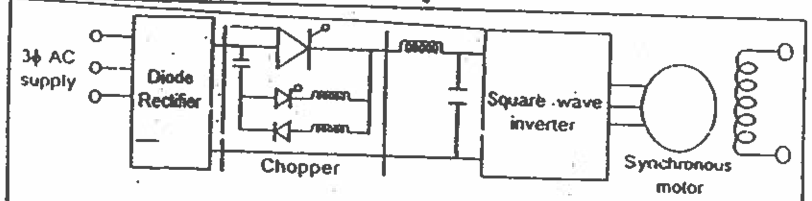


Figure 4.14: Three simple converter to feed varaible voltage and variable frequency to synchronous motor

4.7 Current Source Inverter (CSI) fed Synchronous Motor Drive

As discussed earlier, synchronous motor draws a stator current that is independent of stator frequency when V/f and E/f are maintained constant and the armature resistance is neglected. The motor develops constant flux and torque. So by controlling the stator current, we can have flux and torque control. A synchronous motor can be fed from current source inverter and can have either self control (or) separate control. Due to more stability self control is more preferred by using either rotor position sensing or induced voltage sensing. The motor then operates in CLM mode. When fed from CSI, the synchronous motor can be operated at leading power factor so that the machine voltage can be used for commutation. Thus a load commutated CSI fed synchronous motor is known as converter motor and has good stability characteristics.

Since machine commutation is employed the working speed start typically above 10% of base speed. by using froced commutation the lower speed can be extended till zero.

When load commutation employed the machine is over exciled, the power factor is leading and the machine is less utilized.

The drive has moderate efficiency and is popular as CLM in medium to high power range. There may be voltage spikes in terminal voltage at the instant of commutation, which depend on subtransient leakage reactance of the machine and may affect the insulation.So damper windings can be used to limit these voltage spikes. So CSI fed synchronous motor are always provided with damper windings.

When a synchronous motor is fed from CSI, the motor current are quasi-square wave if the commutation is instantanious. This effect the motor behaviour and also the harmonic present in stator current may cause additional heating losses. They also cause torque pulsations which are unwanted especialy at low speeds.

The CSI is inherently capable of regeneration. Four quadrant operation is very simple and no additional converter is required.

4.7.1 Current source inverters with forced commutation circuits

Forced commutation are provided in the inverter circuit to extend the speed range from zero to base speed. The cost of the inverter increases due to forced commutation circuit. The machine is operated at unity power factor. Efficiency is improved and the drive can be used for low to medium range in CLM mode.

Among all drives possible with synchronous motor, LCI fed synchronous motor is popular in CLM mode. At low speeds the commutation should be assisted. We shall see some of the methods employed for starting and bringing the motor to a speed where the load commutation can take over. As the forced commutation circuitry is required only for low speed the size of the circuit is relatively small.

1) A CSI using individual commutation is very commonly used and is shown in figure 4.15. The motor may be operated at unity power factor. From the figure 4.15 it can be seen that a large inductance is present in the dc link which makes the source current fed to inverter a constant and hence it is a current source inverter. Here each main thyristor is provided with a auxiliary thyristor for commutation purpose.

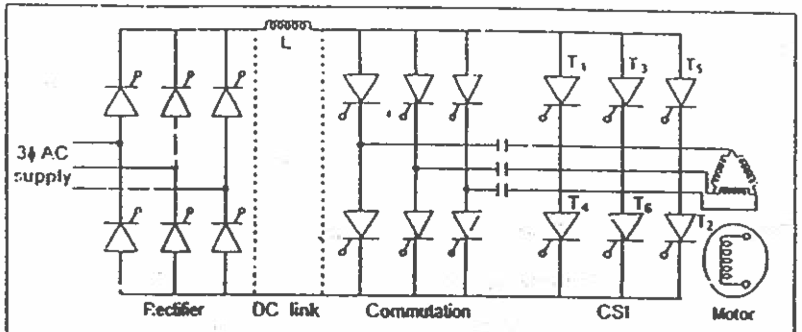


Figure 4.15: CSI with individual commutation

2) Forced commutation at low speeds can also be obtained by means of a Auxiliary Thyristor at the fourth leg of the inverter. A commutating capacitor is connected across the star point and the common point of the two auxiliary thyristors. At low speeds the voltage across the capacitor is used for commutating the main thyristors. Once the machine achieves the speed where load commutation can take place the fourth leg is cut off. This type of inverter is called as third harmonic commutated inverter. It is shown in figure 4.16.

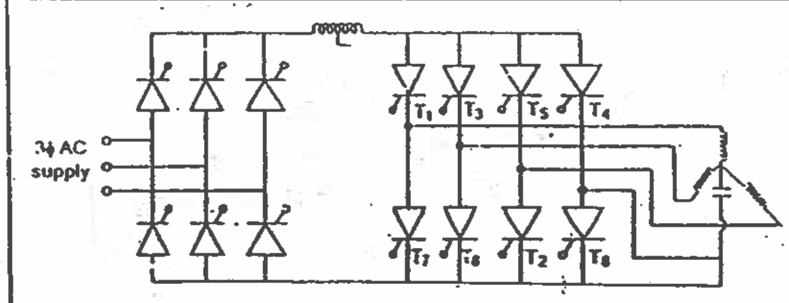


Figure 4.16: Third harmonic commutated ASCSI

3) A kind of artificial quenching is obtained in dc link current interruption at low speeds. The dc link current is interrupted at the instant of commutation and at the same time the line side converter is controlled so that it goes from rectification to inversion. The rotor position sensor sends information to the control unit of the machine side converter to block the firing pulses to the outgoing thyristor and provide to the incoming one. Due to the transition of the line side converter the polarity of the dc link voltage has changed. Consequently the dc link current decays to zero and maintained for a time greater than the turn off time of the thyristors. After this dead zone period the line side converter is again made as a rectifier. The dc link current build up the current and flows through the new thyristros. Similar sequence of operation takes place in other commutations.

The interruption of link current to zero at the instant of commutation and its rising till reference value after commutation are delayed by line inductance. A thyristor is placed across the link inductance to make the current variation faster.

This thyristor is fired at the just the instant when the zero current should exist it ceases conduction, at the end of commutation when the link voltage change it sign. The schematic diagram of connection in shown in figure 4.17.

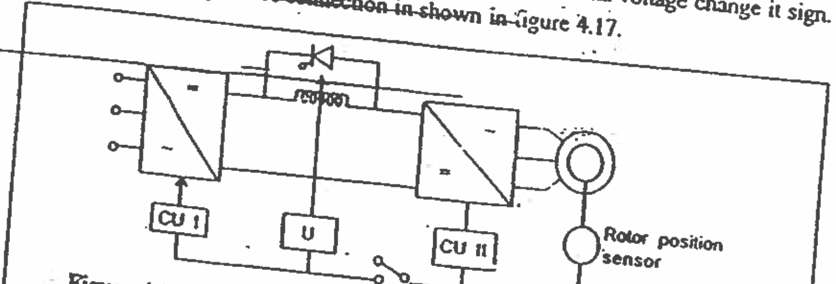


Figure 4.17: DC link control current interruption (Artificial quenching)

4) Small auxiliary motor can be used to run the synchronous motor upto the desired speed when the power is small.

4.8 Synchronous Motor fed from a Cycloconverter

In the synchronous motor fed from VSI (or) CSI,the dc link converter had two stage conversion device that produce variable voltage and variable frequency. Same variable voltage variable frequency can be obtained from a cycloconverter which has single stage conversion. The power circuit of a cycloconverter feeding a synchronous motor is shown in figure 4.18.

The line voltage can be used to commutate the thyristors of a cycloconverter. The output frequency can be varied from 0-1/3 of the input frequency. The ranges of speed control is limited from 0-1/3 of base speed.

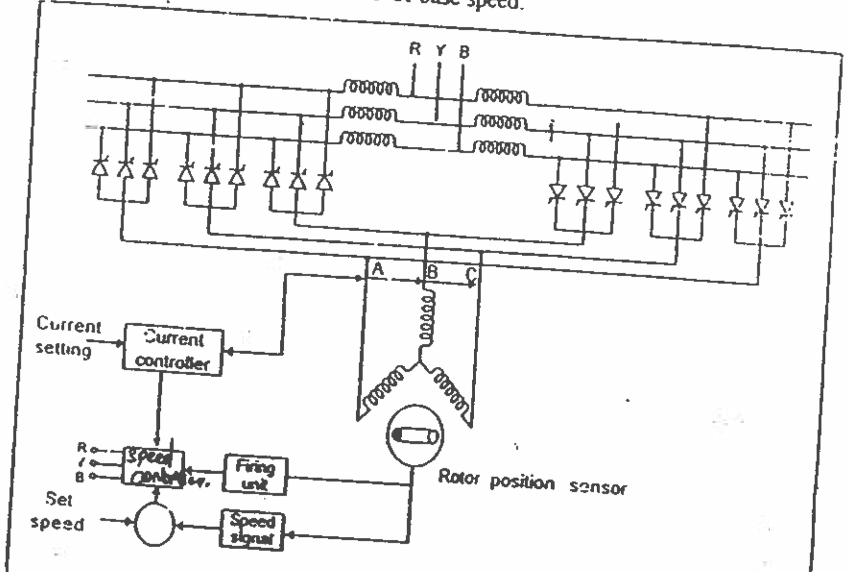


Figure 4.18: Cycloconverter feeding 3-phase SM in self control (CLM Mode)

A cycloconverter can also be commutated using load voltage if the necessary reactive power can be provided for the inverter the load. The machine can be over excited and runs we have load commutated cycloconverter fed synchronous motor. At low speeds upto 10% of base speed, commutation can be assisted by line commutation. Four quadrant operation is simple and straight forward. A cycloconverter gives high quality sinusoidal output voltage and hence the resulting current are also nearly sinusoidal consequently the effect of harmonic current such as losses heating and torque pulsation are minimal when compared to VSI (or) CSI fed drives.

Cycloconverter handle power transfer in both direction. The efficiency is good and also the dynamic behaviour is also good. The CLM mode is popular i.e., self control of synchronous motor using either rotor position sensing (or) induced voltage sensing. The line power-factor is better as the machine power factor can be made unity.

The drawback of the cycloconverter is that it require large number of thyristors and its control circuitry is complex and the converter cost is high. It is preferable for low speed operation and is more commonly used for large low speed reversing mills requiring rapid acceleration and deceleration and also in high power pump and blower type drives.

4.9 Motor Power Factor Control

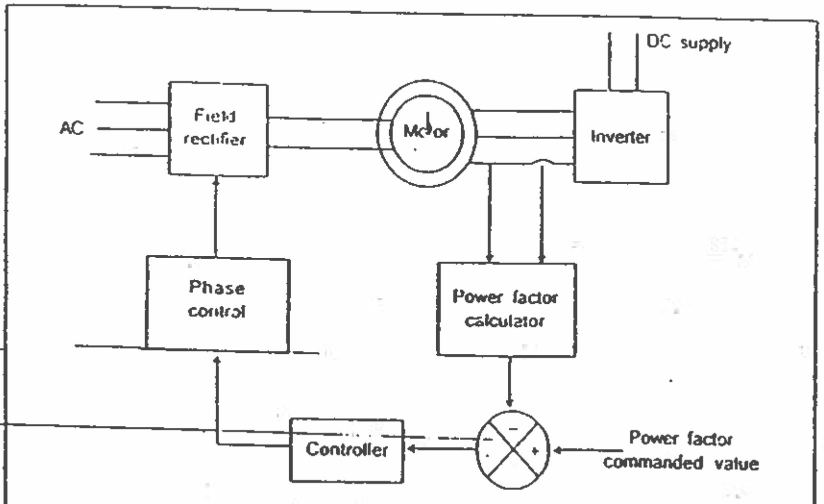


Figure 4.19: Automatic closed loop adjustment of power factor

Figure 4.19 shows the block diagram of automatic closed-loop adjustment of power factor. The main aim of adjustment of power factor is the variation of the field current. This is possible in a wound field machine. If the motor is operated at a power factor of unity, the current drawn by it will have the lowest magnitude for a given power input and therefore the lowest internal copper losses.

From this diagram, the motor voltage and current are sensed and fed to the power factor calculator. The power factor calculator computes the phase angle between the two and therefore the power factor. It is the actual power factor value. The computed power factor value is compared against the power factor commanded value by using error detector.

The error is complified by the error complifier, and its output varies the field current power factor confirm to the commanded value.

4.10 Permanent Magnet Syncronous Motor Drives

Permanent Magnet Synchronous Motors (PMSM) are now commonly known as permanent magnet ac (PMAC) motors. They are classified according to the nature of voltage induced in the stator as sinusoidally excited and trapezoidally excited. These PMAC motors are commonly known as sinusoidal PMAC and trapezoidal PMAC motors.

A sinusoidal PMAC motor has distributed winding (similar to wound field synchronous motor) in the stator side. It employs rotor geometries such as inset or interior shown in figure 4.7. Rotor poles are so shaped that the voltage induced in a stator phase winding has a sinusoidal waveform. The stator of a trapezoidal PMAC motor has concentrated windings and a rotor with a wide pole arc. The voltage induced in the stator phase winding has a trapezoidal waveform. It employs rotor geometries such as surface magnets shown in figure 4.7.

The speed of PMAC motors is controlled by feeding them from variable frequency voltage and currents. They are operated in self-controlled mode of operation. Rotor position sensors are used for operation in self-control mode. Alternatively induced voltage also be used to obtain self-control mode of operation.

Different types of converters and inverters are used to drive the PMAC motors. The current trend is to use MOSFET for low voltage and low power applications and IGBT for medium power applications.

In the past self-controlled mode of operation variable frequency drives employing a sinusoidal PMAC motor were also called brushless dc motor drives. It is also known as sinusoidal PMAC motor drives. The self-controlled variable frequency drives employing a trapezoidal PMAC motor. It is also called brushless dc motor drives or trapezoidal PMAC motor drives.

Sinusoidal PMAC motor drives

Since the voltages produced in the stator of a sinusoidal PMAC motor are sinusoidal, ideally, the three stator phases must be supplied with variable frequency sinusoidal voltages or currents with a phase difference of 120° between them.

Figure 4.20 (a) is the Norton's equivalent of the PMSM equivalent circuit of figure 4.8.

where $$\bar{I}_f = \frac{\bar{E}}{jX_s} = \frac{E}{X_s}\angle -\left(\delta+\frac{\pi}{2}\right) \qquad \text{...(1)}$$

$$\bar{I}_s = \bar{I} + \bar{I}_f \qquad \text{...(2)}$$

voltage source inverter. The inverter is operated to supply motor three phase currents of the magnitude and phase commanded by reference currents i_A^*, i_B^* and i_C^* which are generated by a reference current generator.

The actual motor speed ω_m is compared with reference speed ω_m^*. The speed error $e_{\omega m}$ is processed through the speed controller. The output of the speed controller sets a reference for the amplitude and polarity of the stator current I_s^*. The stator current templates for the three phases are generated by the rotor position sensors in such a way that $\delta' = \pi/2$. When speed error is positive value the machine will work as a motor and the drive will accelerated to reference speed ω_m^*. If speed error is negative value braking will decelerate the motor to reference speed ω_m^*

Since sinusoidal current template is to be generated based on the rotor position, an absolute rotor position sensor or resolver is required, which is expensive. Because of features like excellent dynamic performance, and low torque ripple, the drive is widely used in high performance servo drives inspite of its high cost.

A servo drive for closed-loop position control is obtained by adding a position loop around the speed control loop in figure 4.21.

Trapezoidal PMAC motor drives

The cross section of a 3-phase 2 pole trapezoidal PMAC motor is shown in figure 4.22. It has permanent magnet rotor with wide pole arc. The stator has three concentrated phase windings, which are displaced by 120° and each phase winding spans 60° on each side. The voltages induced in three phases are shown in figure 4.24 (a). The reason for getting the trapezoidal waveforms can be explained.

When revolving in the counter-clockwise direction, up to 120° rotation from the position shown in figure 4.22, all top of the conductors of phase A will be linking the south pole S and all bottom conductors of phase A will be linking the north pole N. Hence the voltage induced in phase A will be the same during 120° rotation (Figure 4.24 (a)). Beyond 120°, some conductors in the top link north pole N and others the south pole S. Same happens with the bottom conductors also. Hence, the voltage induced in phase winding A linearly reverses in next 60° rotation. Rest of the waveform of phase winding A and waveforms of phase winding B and C can be similarly explained.

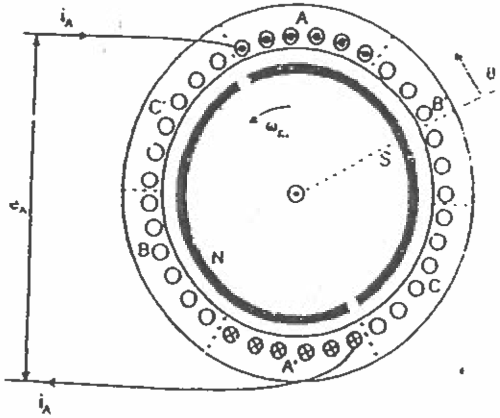


Figure 4.22: Cross section of a trapezoidal PMAC motor

An inverter fed trapezoidal PMAC motor drive operating in self-controlled mode operation is called a brushless dc motor.

Brushless dc motor drive [COMMUTATORLESS DC MOTOR]

Figure 4.23a shows trapezoidal PMAC motor fed from voltage source inverter. The stator windings are connected in star. It has rotor position sensors, which are not shown in figure. The phase voltage waveforms for a trapezoidal PMAC motor are shown in figure 4.24 (a). Let the stator windings be fed with current pulses shown in figure 4.24(b). The current pulses are each of 120° duration and are located in the region where induced voltage is constant and maximum. The polarity of current pulses is the same as that of induced voltage. Since the air-gap flux is contant, the voltage induced is proportional to speed of rotor.

$$E = K_a \omega_m$$

During each 60° interval in figure 4.24, current enters one phase and comes out of another phase, therefore, power supplied to the motor is

$$P = EI_d + (-E)(-I_d) = 2EI_d = 2K_a\omega_m I_d$$

Torque developed by the motor

$$T = \frac{P}{\omega_m} = 2K_a I_d = K_T I_d$$

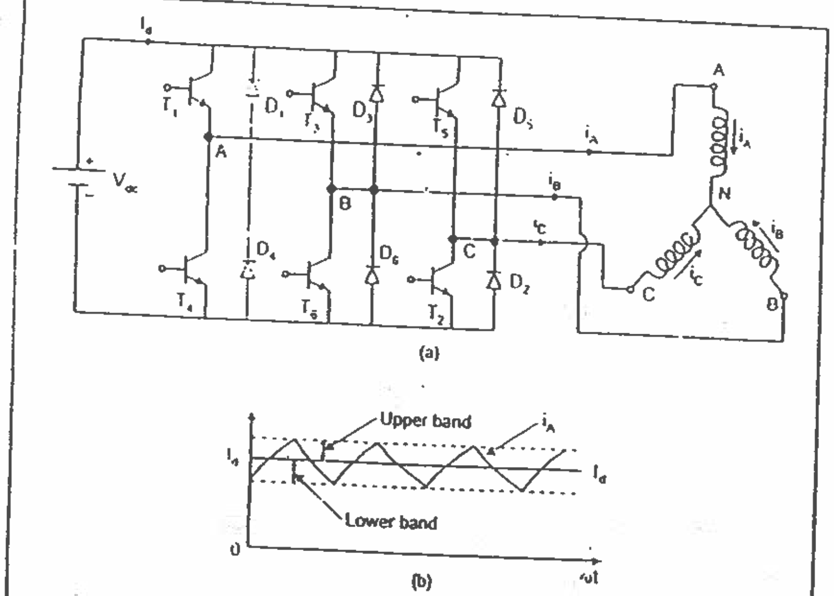


Figure 4.23: Trapezoidal PMAC motor fed from a current regulated voltage source inverter

The waveform of torque is given in figure 4.24(c). According to the torque equation, torque is proportional to current I_d. DC current I_d flows in the dc link. Regenerative braking mode of operation is obtained by reversing phase currents. This will also reverse the source current I_d. Now power flows from the machine to inverter and from inverter to dc source.

When motor speed is reversed, the polarity of induced voltages also reverse. With current polarity shown in figure 4.24, the drive gives regenerative braking mode of operation; and when current direction is reversed motoring operation is obtained. The current waveform shown in figure 4.24 are produced as follows.

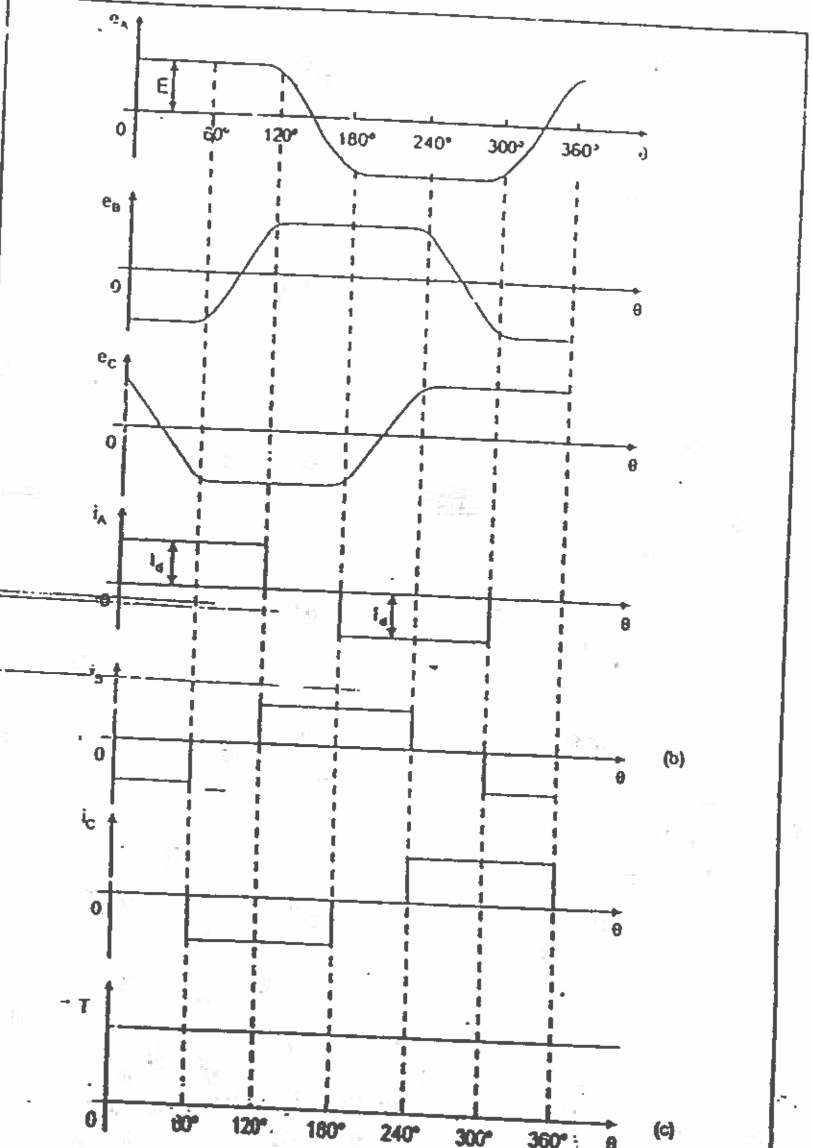


Figure 4.24: Induced voltage, phase current and torque waveforms of a trapezoidal PMAC motor

During the period of 0° to 60°, $i_A = I_d$ and $i_B = -I_d$. The current i_A enters through the phase winding A and leaves through the phase winding B.

When power transistors T_1 and T_6 are on state, terminals A and B are respectively connected to positive and negative terminals of the dc source V_{dc}.

A current will flow through the path consisting of V_{dc}, T_1, phase A, phase B and T_6 and rate of change of current i_A will be positive.

When T_1, phase winding A, phase winding B and T_6 are turned off this current will flow through a path consisting of phase A, phase B, diode D_3, V_{dc} and diode D_4.

Since the current has to flow against voltage V_{dc}, the rate of change of i_A will be negative.

The turning on and off T_1 and T_6, phase winding A current can be made to follow the reference current I_d within a hysteresis band as shown in figure 4.23(b). The operation for other 60° intervals can be similarly explained.

For properly connecting the current pulses with respect to induced voltages, or identification of these sixty-degree intervals, signals are generated by rotor position sensors. In all six rotor angular positions are required to be detected cycle of the induced voltage.

The Hall effect sensors can detect the magnitude and direction of a magnetic field Hence three Hall-effect sensors can be detect the six rotor positions.

The sensors are mounted at 60° electrical interval and aligned suitably with the stator winding. Optical sensors are also be used.

The trapezoidal PMAC drive is mainly used in servo derives. Sinusoidal PMAC drive is mainly used in high performance drives.