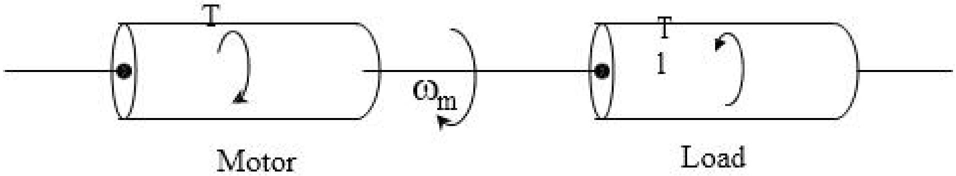
UNIT-II
FOUR QUADRANT OPERATION OF DC DRIVES THROUGH DUAL CONVERTER

Dynamics of Motor Load System

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

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

Equivalent rotational system of motor and load is shown in the figure.



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

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

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

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

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

$$T-T_l = d/dt\,(J\,\omega_m) = J\,d/dt\,(\omega_m) + \omega_m\,dJ/dt \qquad \ldots\ldots\ldots\ldots\ (1)$$

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

For drives with constant inertia

$$\frac{dJ}{dt}=0$$

$$T=T_l + J\,d/dt\,(\omega_m) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Equation (2) shows that torque developed by motor

Classification of Load Torques:

Various load torques can be classified into broad categories.

- ✓ Active load torques
- ✓ Passive load torques

Load torques which has the potential to drive the motor under equilibrium conditions are called active load torques. Such load torques usually retain their sign when the drive rotation is changed (reversed)

Eg:

- ✓ Torque due to force of gravity
- ✓ Torque due tension
- ✓ Torque due to compression and torsion etc

Load torques which always oppose the motion and change their sign on the reversal of motion are called passive load torques

Eg:

- ✓ Torque due to friction, cutting etc.

Components of Load Torques:

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

✓ Friction Torque (T_F):

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

✓ Windage Torque (T_W)

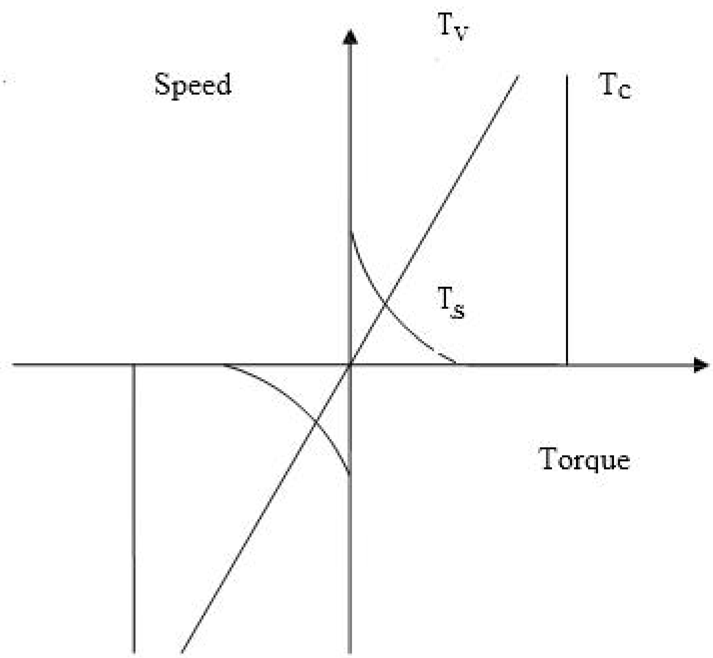
When motor runs, wind generates a torque opposing the motion. This is known as windage torque.

✓ Torque required to do useful mechanical work

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

Friction at zero speed is called diction or static friction. In order to start the drive the motor should at least exceeds diction.

Friction torque can also be resolved into three components



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

$$T_V = B\,\omega_m$$

Where B is viscous friction co-efficient.

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

$$T_W = C\,\omega_m^2$$

From the above discussions, for finite speed

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

Characteristics of Different types of Loads

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

Constant torque type load

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

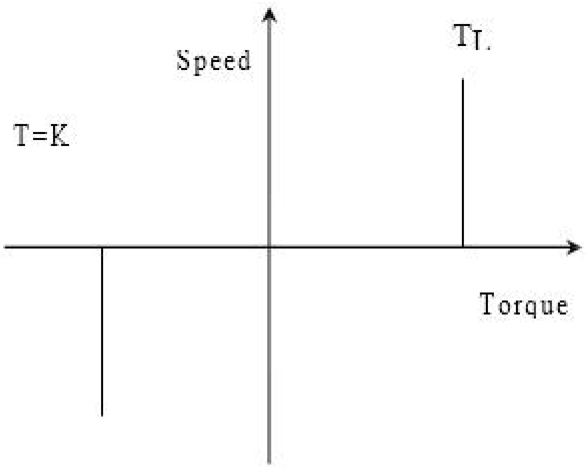
Constant Torque characteristics:

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

Torque Proportional to speed:

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

$$T=k$$

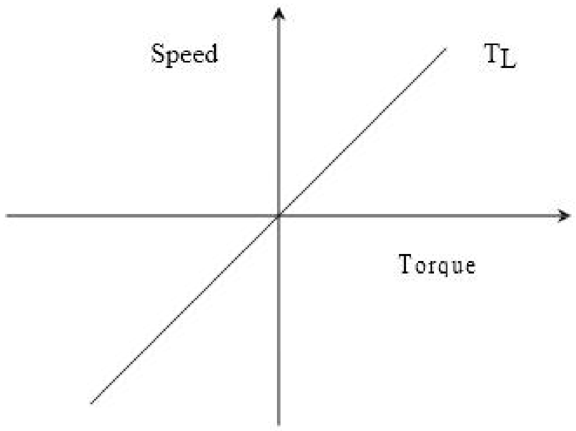


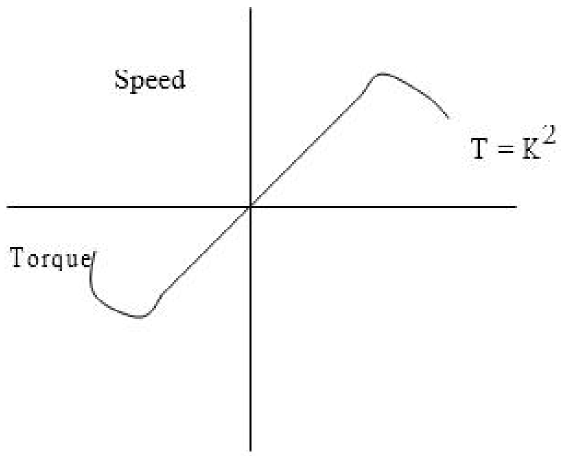
Torque proportional to square of the speed:

Another type of load met in practice is the one in which load torque is proportional to the square of the speed.

Examples:

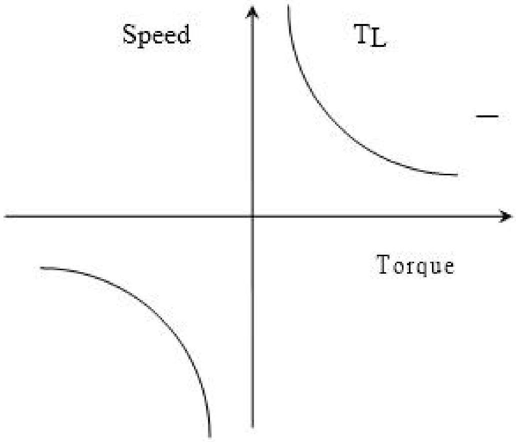
- ✓ Fans rotary pumps,
- ✓ Compressors
- ✓ Ship propellers





Torque Inversely proportional to speed:

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



Multi quadrant Operation:

For consideration of multi quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed.

A motor operates in two modes – Motoring and braking. In motoring, it converts electrical energy into mechanical energy, which supports its motion. In braking it works as a generator converting mechanical energy into electrical energy and thus opposes the motion.

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

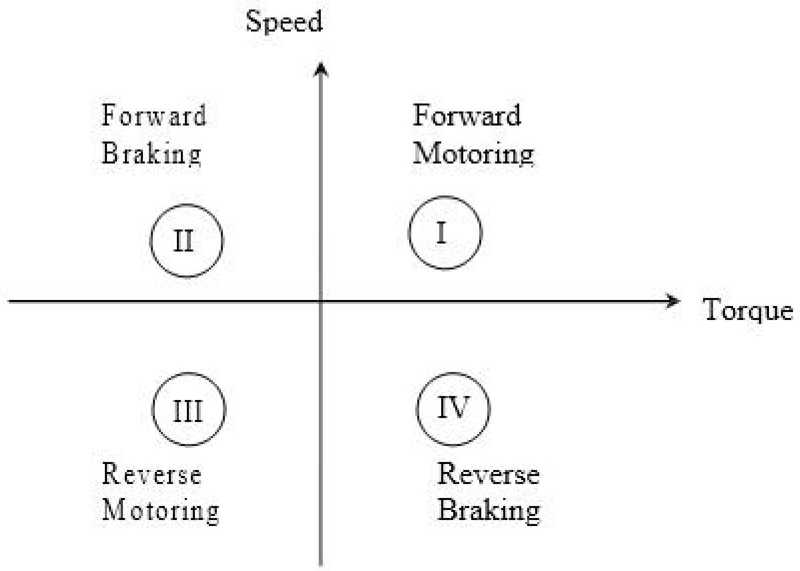
Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B

Similarly operation in quadrant III and IV can be identified as reverse motoring and reverse braking since speed in these quadrants is negative.

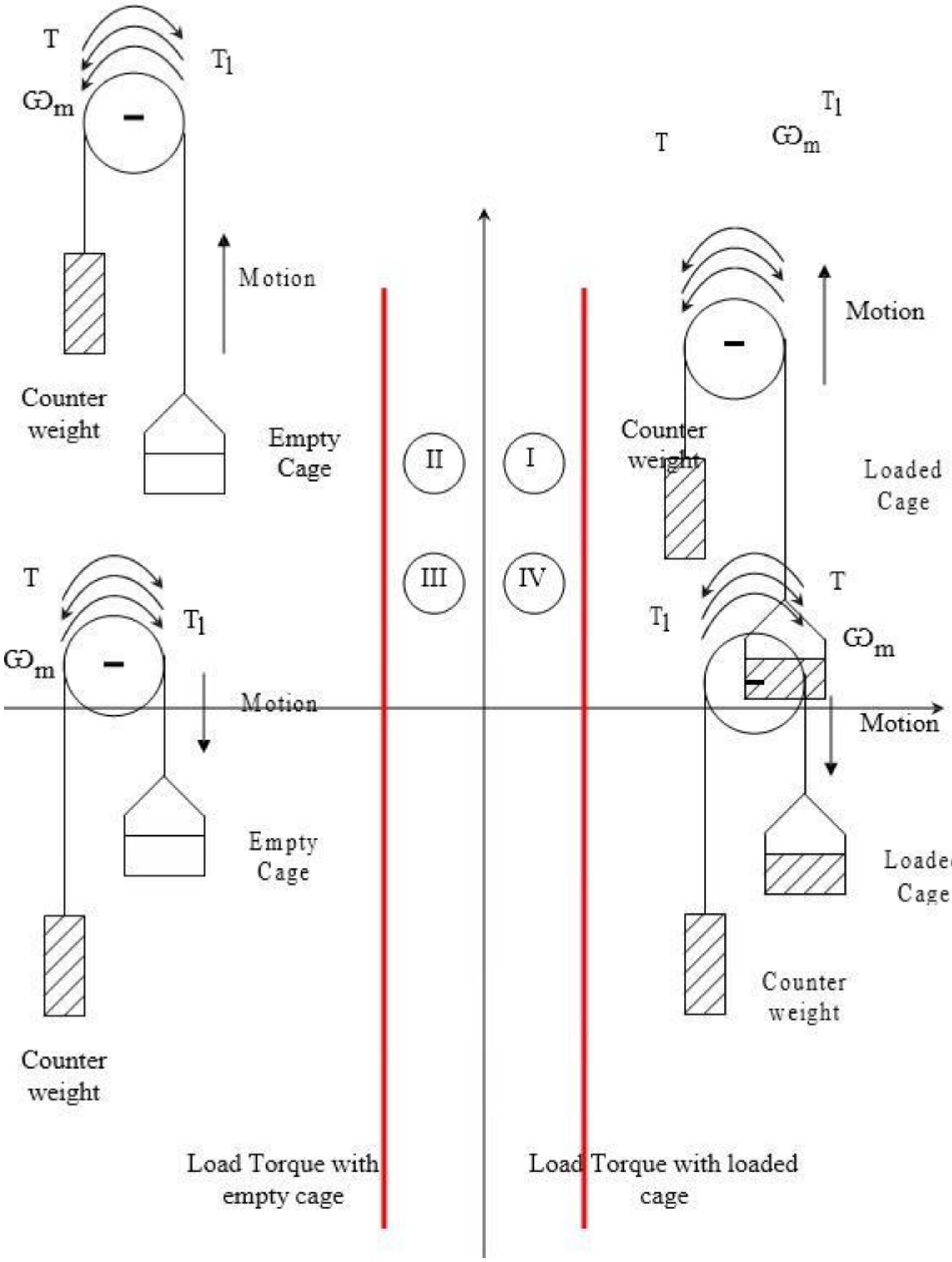
For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction of motor and load torques and direction of speed are marked by arrows

The figure at the right represents a DC motor attached to an inertial load. Motor can provide motoring and braking operations for both forward and reverse directions.

Figure shows the torque and speed co-ordinates for both forward and reverse motions. Power developed by a motor is given by the product of speed and torque. For motoring operations Power developed is positive and for braking operations power developed is negative.



For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction of motor and load torques and direction of speed are marked by arrows.



A hoist consists of a rope wound on a drum coupled to the motor shaft one end of the rope is tied to a cage which is used to transport man or material from one level to another level . Other end of the rope has a counter weight. Weight of the counter weight is chosen to be higher than the weight of empty cage but lower than of a fully loaded cage.

Forward direction of motor speed will be one which gives upward motion of the cage. Load torque line in quadrants I and IV represents speed-torque characteristics of the loaded hoist. This torque is the difference of torques due to loaded hoist and counter weight. The load torque in quadrants II and III is the speed torque characteristics for an empty hoist.

This torque is the difference of torques due to counter weight and the empty hoist. Its sigh is negative because the counter weight is always higher than that of an empty cage. The quadrant I operation of a hoist requires movement of cage upward, which corresponds to the positive motor speed which is in counter clockwise direction here. This motion will be obtained if the motor products positive torque in CCW direction equal to the magnitude of load torque T_{L1}.

Since developed power is positive, this is forward motoring operation. Quadrant IV is obtained when a loaded cage is lowered. Since the weight of the loaded cage is higher than that of the counter weight .It is able to overcome due to gravity itself.

In order to limit the cage within a safe value, motor must produce a positive torque T equal to T_{L2} in anticlockwise direction. As both power and speed are negative, drive is operating in reverse braking operation. Operation in quadrant II is obtained when an empty cage is moved up. Since a counter weigh is heavier than an empty cage, its able to pull it up.

In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{L2} in clockwise direction. Since speed is positive and developed power is negative, it's forward braking operation.

Operation in quadrant III is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in CW direction. Since speed is negative and developed power is positive, this is reverse motoring operation. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient state operation.

Braking and its classification

The term braking comes from the term brake. We know that brake is an equipment to reduce the speed of any moving or rotating equipment, like vehicles, locomotives. The process of applying brakes can be termed as braking. Now coming to the term or question **what is braking**. First of all we can classify the term braking in two parts i) mechanical braking and the ii) electrical braking. Mechanical braking is left out here because as it is an electrical engineering site, we should only focus on electrical braking here. In mechanical braking the speed of the machine is reduced solely by mechanical process but electrical braking is far more interesting than that because the whole process is depended on the flux and torque directions. We will further see through the various types of braking but the main idea behind each type of barking is the reversal of the direction of the flux. So, we can understand that when it is asked that **what is braking**? We can say that it is the process of reducing speed of any rotating machine. The application of braking is seen at almost every possible area, be it inside the motor used in factories, industrial areas or be it in locomotives or vehicles. Everywhere the use of mechanical and electrical brakes is inevitable.

Types of Braking

Brakes are used to reduce or cease the speed of motors. We know that there are various types of motors available (DC motors, induction motors, synchronous motors, single phase motors etc.) and the specialty and properties of these motors are different from each other, hence this braking methods also differs from each other. But we can divide braking in to three parts mainly, which are applicable for almost every type of motors.

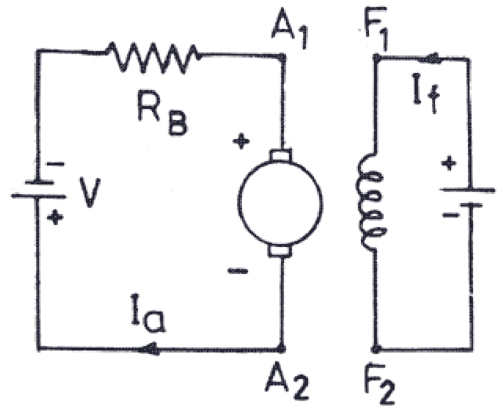
i) Regenerative Braking
ii) Plugging type braking
iii) Dynamic braking.

Regenerative Braking

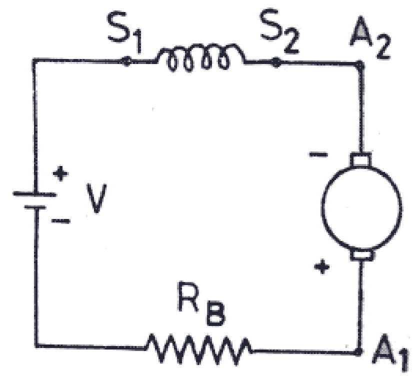
Regenerative braking takes place whenever the speed of the motor exceeds the synchronous speed. This baking method is called regenerative braking because here the motor works as generator and supply itself is given power from the load, i.e. motors. The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed, only then the motor will act as a generator and the direction of current flow through the circuit and direction of the torque reverses and braking takes place. The only disadvantage of this type of braking is that the motor has to run at super synchronous speed which may damage the motor mechanically and electrically, but regenerative braking can be done at sub synchronous speed if the variable frequency source is available.

Plugging Type Braking

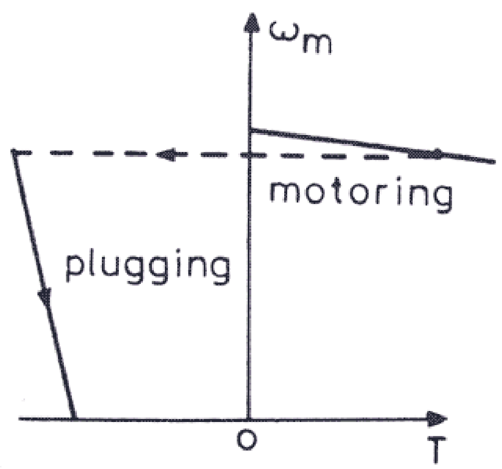
Another type of braking is **Plugging type braking**. In this method the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases. During plugging external resistance is also introduced into the circuit to limit the flowing current. The main disadvantage of this method is that here power is wasted.



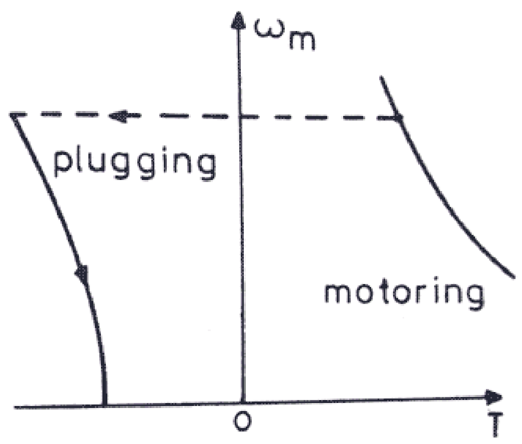
Separately excited



Series



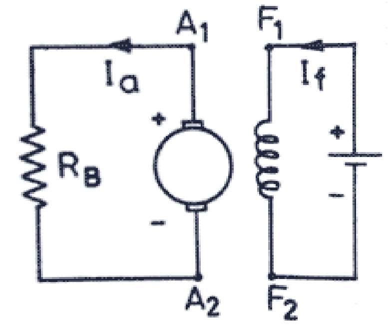
Separately excited



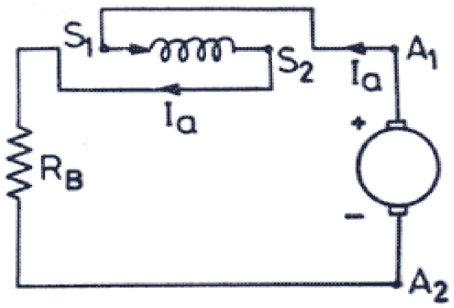
Series

Dynamic Braking

Another method of reversing the direction of torque and braking the motor is **dynamic braking**. In this method of braking the motor which is at a running condition is disconnected from the source and connected across a resistance. When the motor is disconnected from the source, the rotor keeps rotating due to inertia and it works as a self –excited generator. When the motor works as a generator the flow of the current and torque reverses. During braking to maintain the steady torque sectional resistances are cut out one by one.



Separately excited motor



Series motor

Basics of Regenerative Braking

In the regenerative braking operation, the motor operates as generator, while it is still connected to the supply. Here, the motor speed is greater than the synchronous speed.

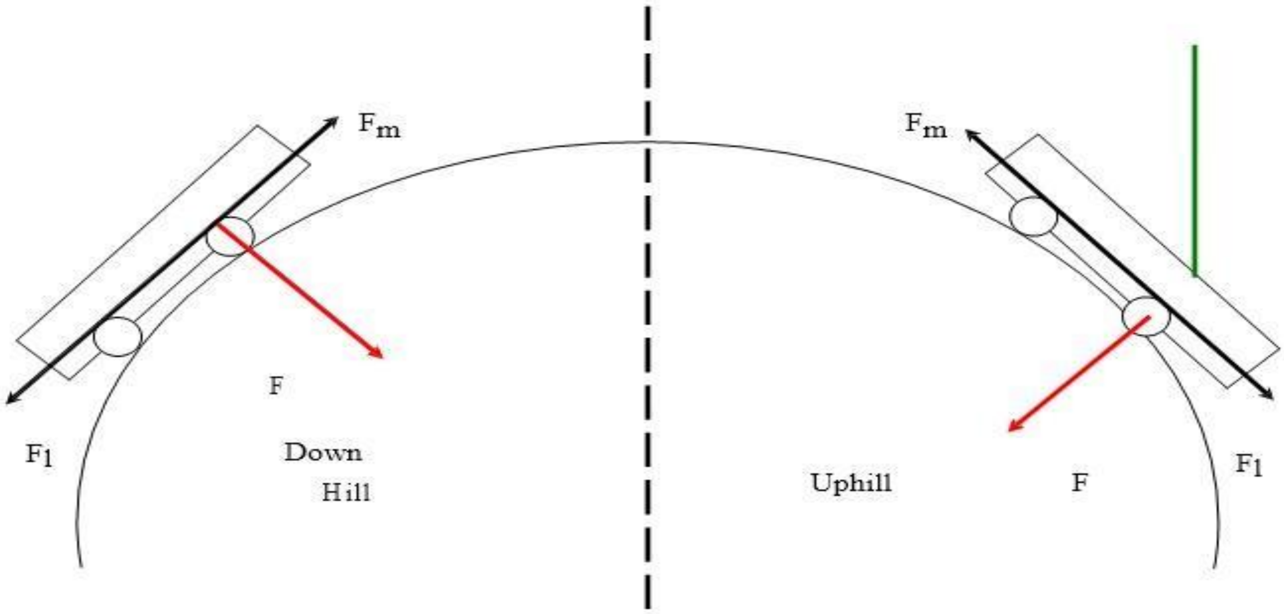
Mechanical energy is converted into electrical energy, part of which is returned to the supply and rest of the energy is last as heat in the winding and bearings of electrical machines pass smoothly from motoring region to generating region, when over driven bythe load.

An example of regenerative braking is shown in the figure below. Here an electric motor is driving a trolley bus in the uphill and downhill direction. The gravity force can be resolved into two components in the uphill direction.

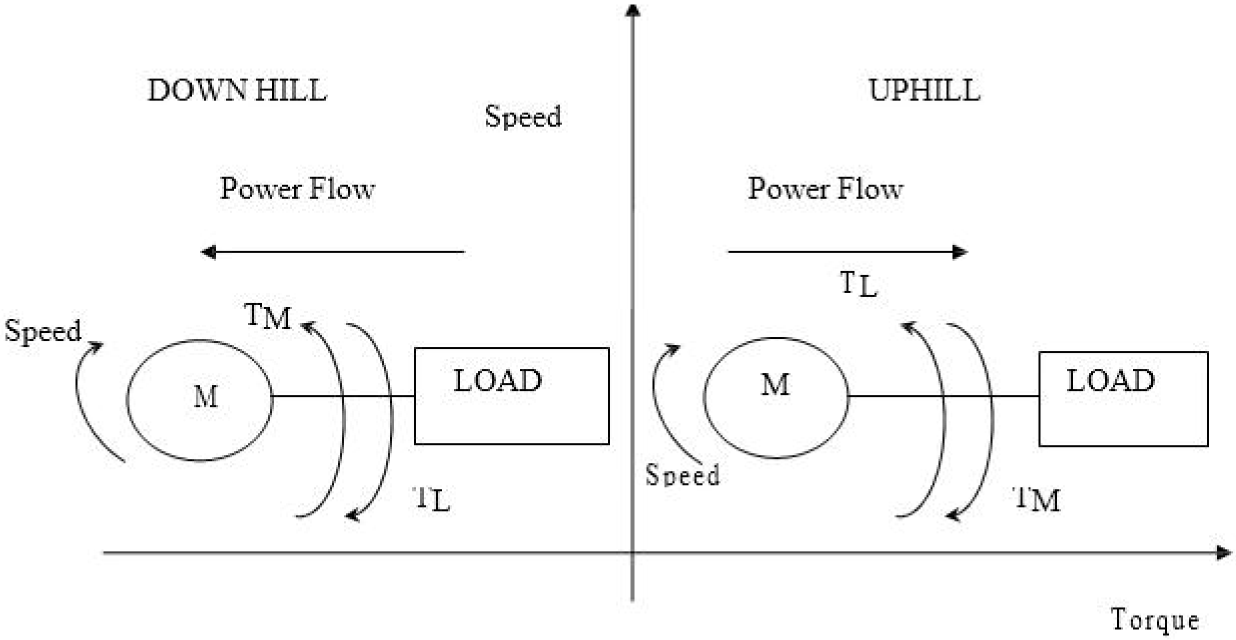
One is perpendicular to the load surface (F) and another one is parallel to the road surface Fl. The parallel force pulls the motor towards bottom of the hill.

If we neglect the rotational losses, the motor must produce force Fm opposite to Fl to move the bus in the uphill direction.

Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power flows from mechanical load to source.



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



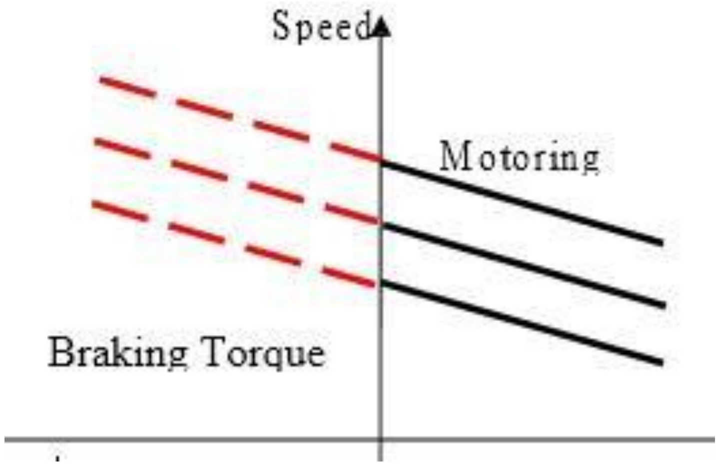
Now we consider that the same bus is traveling in downhill, the gravitational force doesn't change its direction but the load torque pushes the motor towards the bottom of the hill. The motor produces a torque in the reverse direction because the direction of the motor torque is always opposite to the direction of the load torque.

Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power flows from mechanical load to source. Hence, the load is driving the machine and the machine is generating electric power that is returned to the supply.

Regenerative Braking for DC motor:

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

$E > V$ and I_a should be negative



Modes of Operation:

An electrical drive operates in three modes

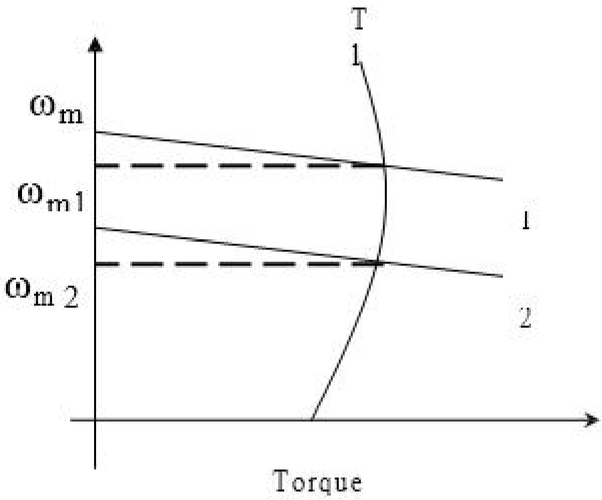
- ✓ Steady state
- ✓ Acceleration including Starting
- ✓ Deceleration including Stopping

We know that

$$T=T_1 + J\ d/dt\ (\omega_m)$$

According to the above expression the steady state operation takes place when motor torque equals the load torque. The steady state operation for a given speed is realized by adjustment of steady state motor speed torque curve such that the motor and load torques are equal at this speed. Change in speed is achieved by varying the steady state motor speed torque curve so that motor torque equals the load torque at the new desired speed. In the figure shown below when the motor parameters are adjusted to provide speed torque curve 1, drive runs at the desired speed $\omega_{m\ 1}$.

Speed is changed to $\omega_{m\ 2}$ when the motor parameters are adjusted to provide speed torque curve 2. When load torque opposes motion, the motor works as a motor operating in quadrant I or III depending on the direction of rotation. When the load is active it can reverse its sign and act to assist the motion. Steady state operation for such a case can be obtained by adding a mechanical brake which will produce a torque in a direction to oppose the motion. The steady state operation is obtained at a speed for which braking torque equal the load torque. Drive operates in quadrant II or IV depending upon the rotation.



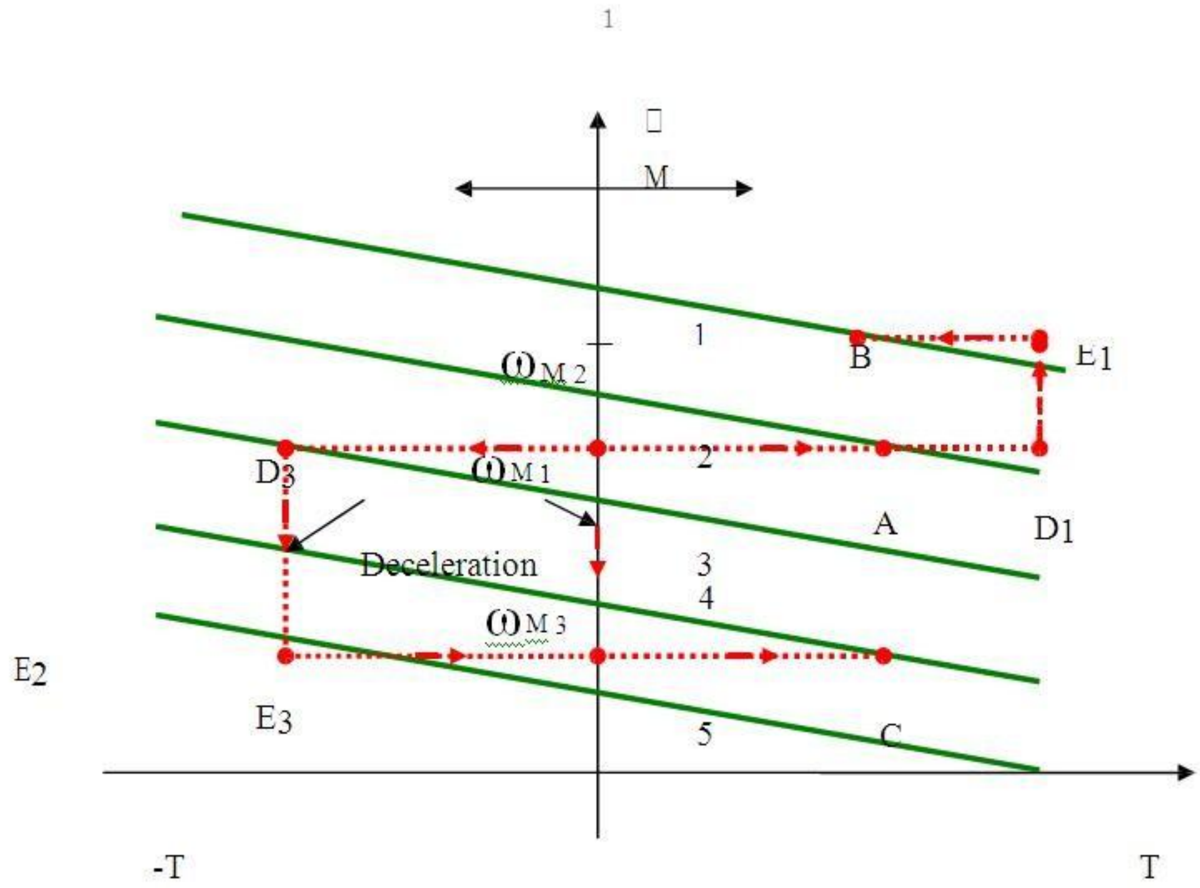
Acceleration and Deceleration modes are transient modes. Drive operates in acceleration mode whenever an increase in its speed is required. For this motor speed torque curve must be changed so that motor torque exceeds the load torque. Time taken for a given change in speed depends on inertia of motor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

Increase in motor torque is accompanied by an increase in motor current. Care must be taken to restrict the motor current with in a value which is safe for both motor and power modulator. In applications involving acceleration periods of long duration, current must not be allowed to exceed the rated value. When acceleration periods are of short duration a current higher than the rated value is allowed during acceleration.

In closed loop drives requiring fast response, motor current may be intentionally forced to the maximum value in order to achieve high acceleration. Figure shown below shows the transition from operating point A at speed.

Point B at a higher speed ω_{m2}, when the motor torque is held constant during acceleration. The path consists of AD1E1B. In the figure below, 1 to 5 are motor speed torque curves. Starting is a special case of acceleration where a speed change from 0 to a desired speed takes place. All points mentioned in relation to acceleration are applicable to starting.

The maximum current allowed should not only be safe for motor and power modulator but drop in source voltage caused due to it should also be in acceptable limits. In some applications the motor should accelerate smoothly, without any jerk. This is achieved when the starting torque can be increased step lessly from its zero value. Such a start is known as soft start.



Four Quadrant Operation of a Converters

Separately-excited dc shunt motor can be operated in either direction in either of the two modes, the two modes being the motoring mode and the regenerating mode. It can be seen that the motor can operate in any of the four quadrants and the armature of the dc motor in a fast four-quadrant drive is usually supplied power through a dual converter. The dual converter can be operated with either circulating current or without circulating current. If both the converters conduct at the same time, there would be circulating current and the level of circulating current is restricted by provision of an inductor. It is possible to operate only one converter at any instant, but switching from one converter to the other would be carried out after a small delay. This page describes the operation of a dual converter operating without circulating current.

As shown in Fig. 1, the motor is operated such that it can deliver maximum torque below its base speed and maximum power above its base speed. To control the speed below its base speed, the voltage applied to the armature of motor is varied with the field voltage held at its nominal value. To control the speed above its base speed, the armature is supplied with its rated voltage and the field is weakened. It means that an additional single-phase controlled rectifier circuit is needed for field control. Closed-loop control in the field-weakening mode tends to be difficult because of the relatively large time constant of the field.

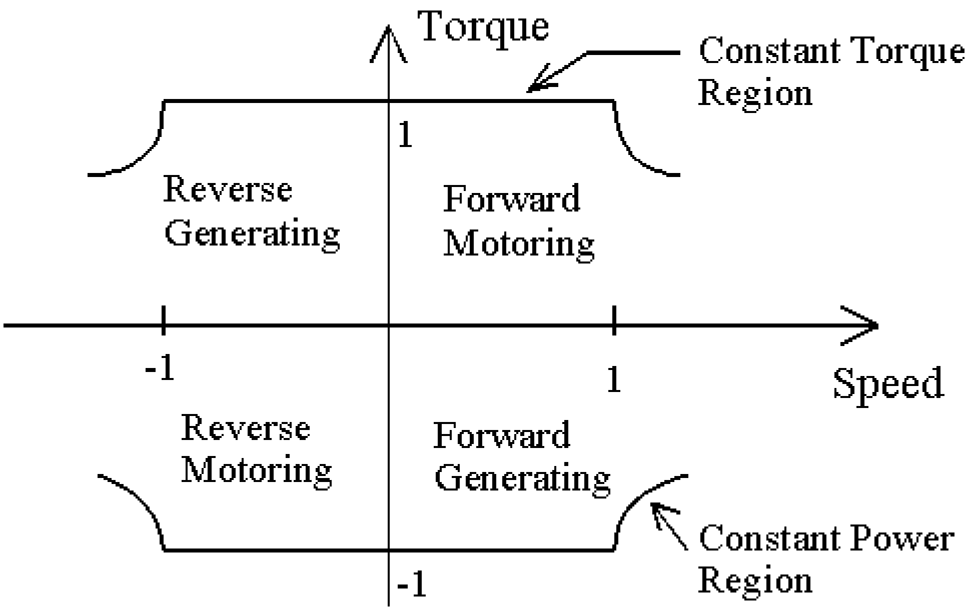


Fig. 1: Speed-Torque characteristic

The power circuit of the dual-converter dc drive is shown in Fig. 2.

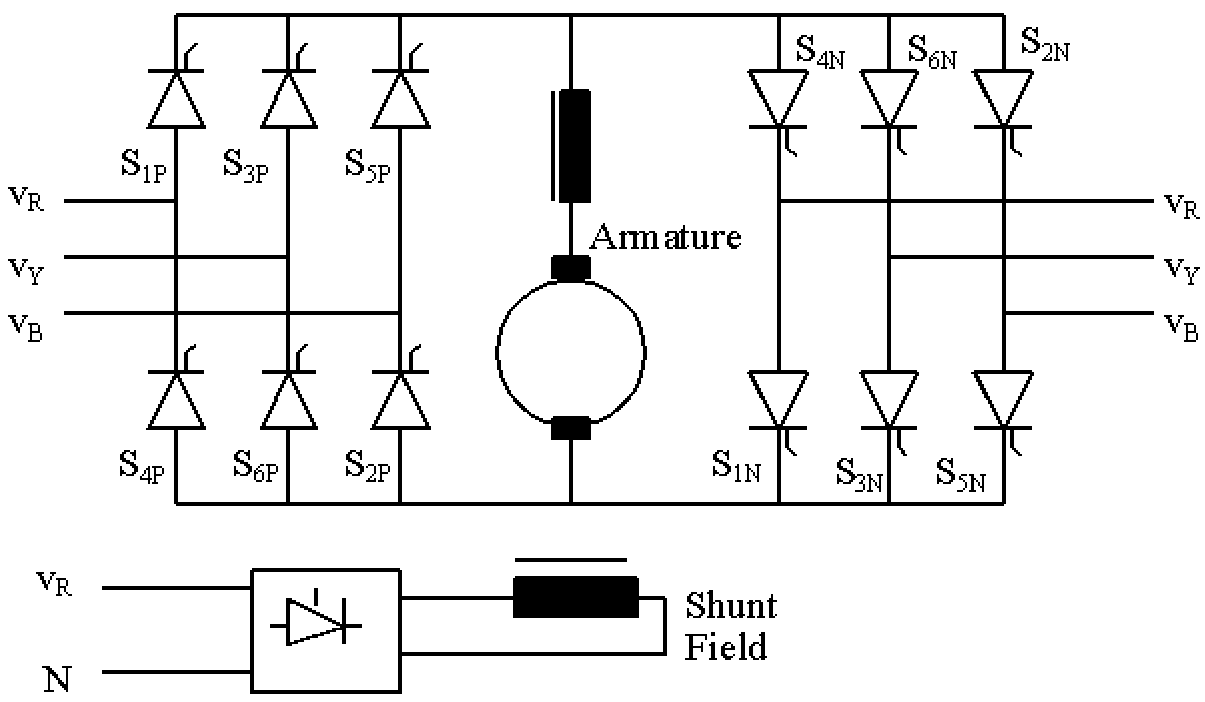


Fig. 2: Power Circuit

Each converter has six SCRs. The converter that conducts for forward motoring is called the positive converter and the other converter is called the negative converter. The names given are arbitrary. Instead of naming the converters as positive and negative converter, the names could have been the forward and reverse converter. The field is also connected to a controlled-bridge in order to bring about field weakening.

The circuit shown above can be re-drawn as shown in Fig. 3. Usually an inductor is inserted in each line as shown in Fig. 3 and this inductor reduces the impact of notches on line voltages that occur during commutation overlap.

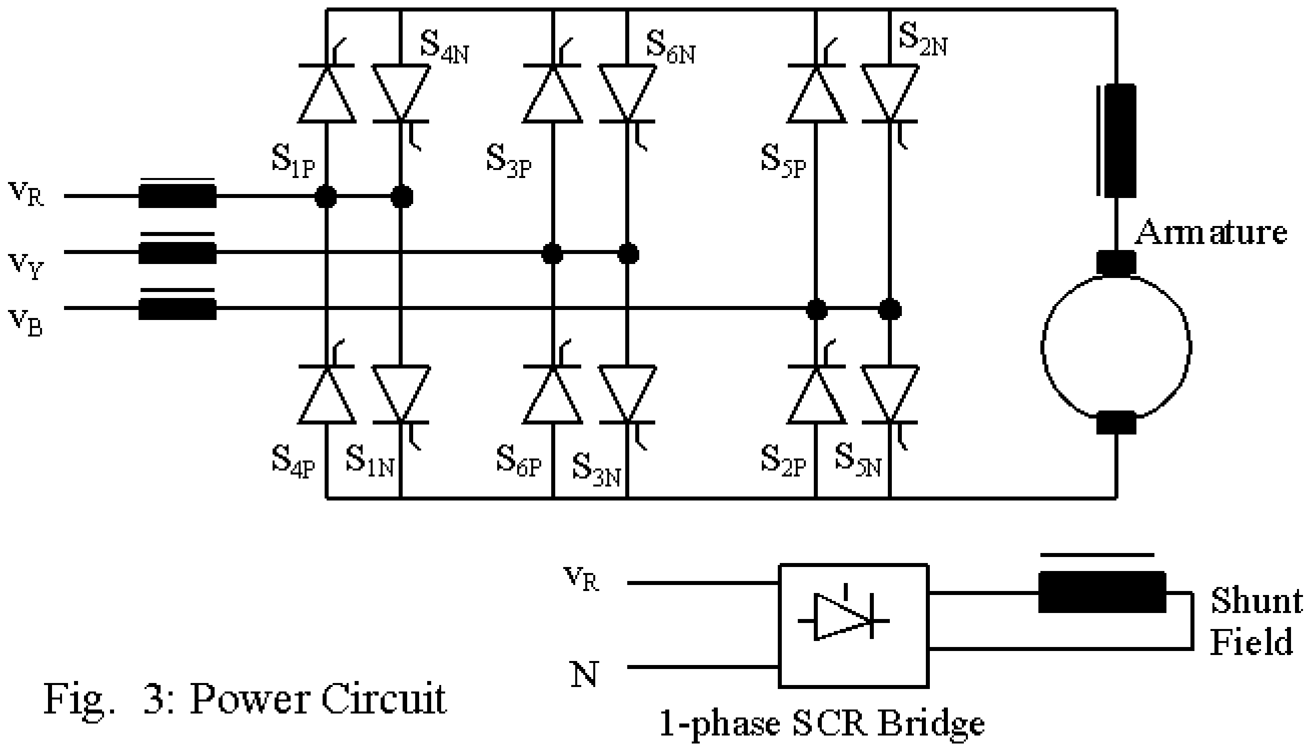


Fig. 3: Power Circuit

CIRCUIT OPERATION

The operation of the circuit in the circulating-current free mode is not very much different from that described in the previous pages. In order to drive the motor in the forward direction, the positive converter is controlled. To control the motor in the reverse direction, the negative converter is controlled. When the motor is to be changed fast from a high value to a low value in the forward direction, the conduction has to switch from the positive converter to the negative converter. Then the direction of current flow changes in the motor and it regenerates, feeding power back to the source. When the speed is to be reduced in the reverse direction,

the conduction has to switch from the negative converter to the positive converter. The conduction has to switch from one converter to the other when the direction of motor rotation is to change.

At the instant when the switch from one converter to the other is to occur, it would be preferable to ensure that the average output voltage of either converter is the same. Let the firing angle of the positive converter be a_P, and the firing angle of the negative converter be a_N. If the peak line voltage be U, then equation (1) should apply. Equation (1) leads to equation (2). Then the sum of firing angles of the two converters is p, as shown in equation (3).

$$\frac{3U}{\pi} \times \mathrm{Cos}\ (\alpha_P) = -\ \frac{3U}{\pi} \times \mathrm{Cos}\ (\alpha_N) \quad (1)$$

$$\mathrm{Cos}\ (\alpha_P) = \mathrm{Cos}\ (\pi - \alpha_N) \quad (2)$$

$$\alpha_P + \alpha_N = \pi \quad (3)$$

In a dual-converter, the firing angles for the converter are changed according to equation (3). But it needs to be emphasized that only one converter operates at any instant.

When the speed of the motor is to be increased above its base speed, the voltage applied to the armature is kept at its nominal value and the phase-angle of the single phase bridge is varied such that the field current is set to a value below its nominal value. If the nominal speed of the motor is 1500 rpm, then the maximum speed at which it can run cannot exceed a certain value, say 2000 rpm. Above this speed, the rotational stresses can affect the commutator and the motor can get damaged.