

8. DC Drives

This senior part of electrical engineering introduces the principles of combining Electrical Machines with Power Electronics Converters. This combination is commonly known as Electrical Drives. However, Electrical Drives can be classified as DC Drives and AC Drives. In this lecture, we shall consider DC drives only.

1. Power Semiconductor Drive and its Elements

The basic arrangement of an electrical drive is shown in Fig.8.1. The block diagram of this DC drive is shown in Fig.8.2.

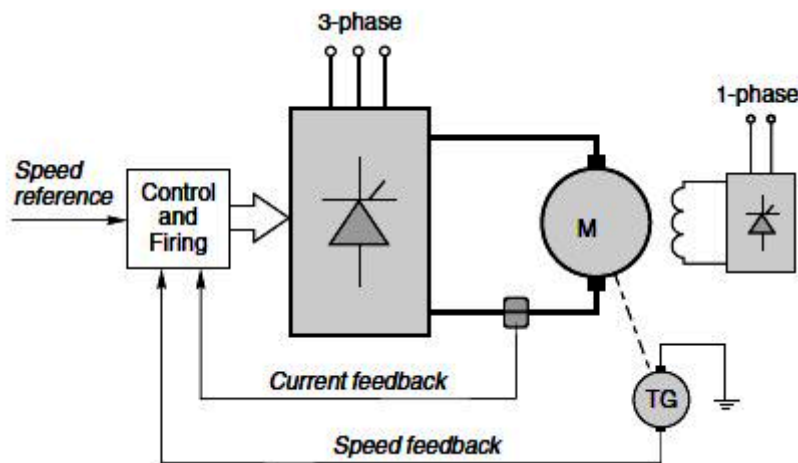


Fig.8.1 Schematic diagram of speed-controlled d.c. motor drive.

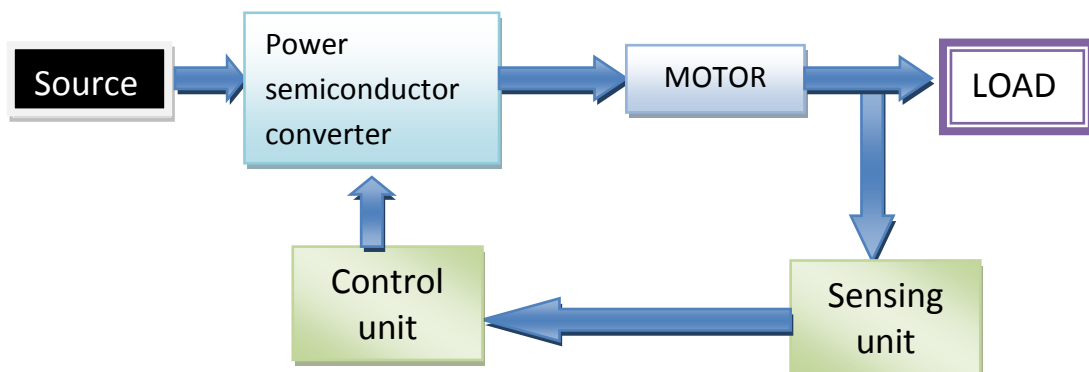


Fig.8.2 Block diagram of the d.c. drive.

For motors up to a few kilowatts the armature circuit of the motor can be supplied from either single-phase or three-phase mains, but for larger motors three-phase is always used. A separate thyristor or diode rectifier is used to supply the field of the motor: the power is much less than the armature power, so the supply is often single-phase, as shown in Figure 8.1. An example of actual DC drive circuit with the armature of the motor supplied from a three-phase full-wave fully controlled rectifier is shown in fig.8.3.

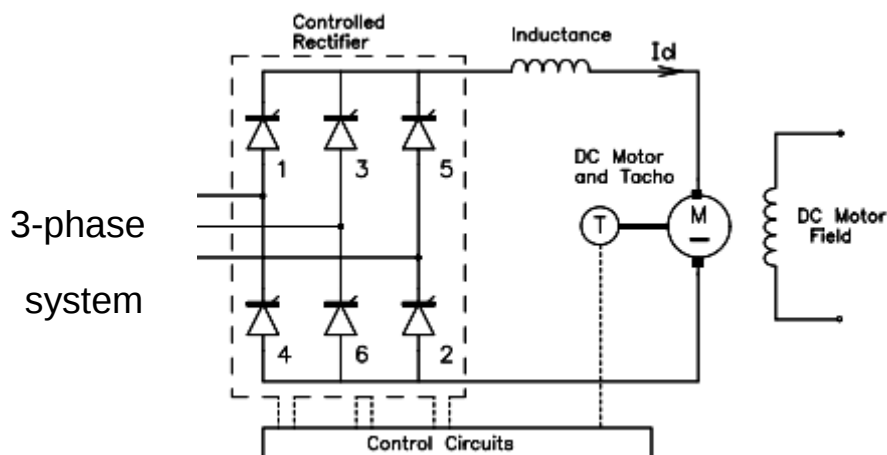
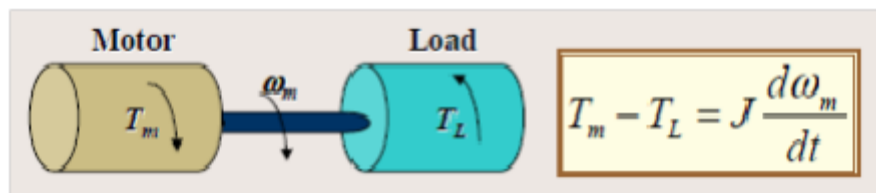


Fig.8.3 Example of actual DC drive circuit

2. Dynamics of the Load System



J = polar moment of inertia of motor-load system referred to the motor shaft, Kg.m²

ω_m = instantaneous angular velocity of the motor shaft, rad / sec

$T_m = T_d$ = developed torque of the motor, N.m

T_L = load (resisting) torque, referred to the motor shaft, N.m

Note:

At steady-state: $\frac{d\omega_m}{dt} = 0 \Rightarrow T_m = T_L$

$J \frac{d\omega_m}{dt} = \text{Dynamic torque}$

$T_m > T_L$: acceleration

$T_m < T_L$: deceleration

In this course notes we shall consider the motor – drive system operation in the steady – state only.

3. Review of DC Motor Theory

DC motor construction:

Dc motor is mainly constructed from two main parts, the stator and the rotor as shown in Fig.8. 4.

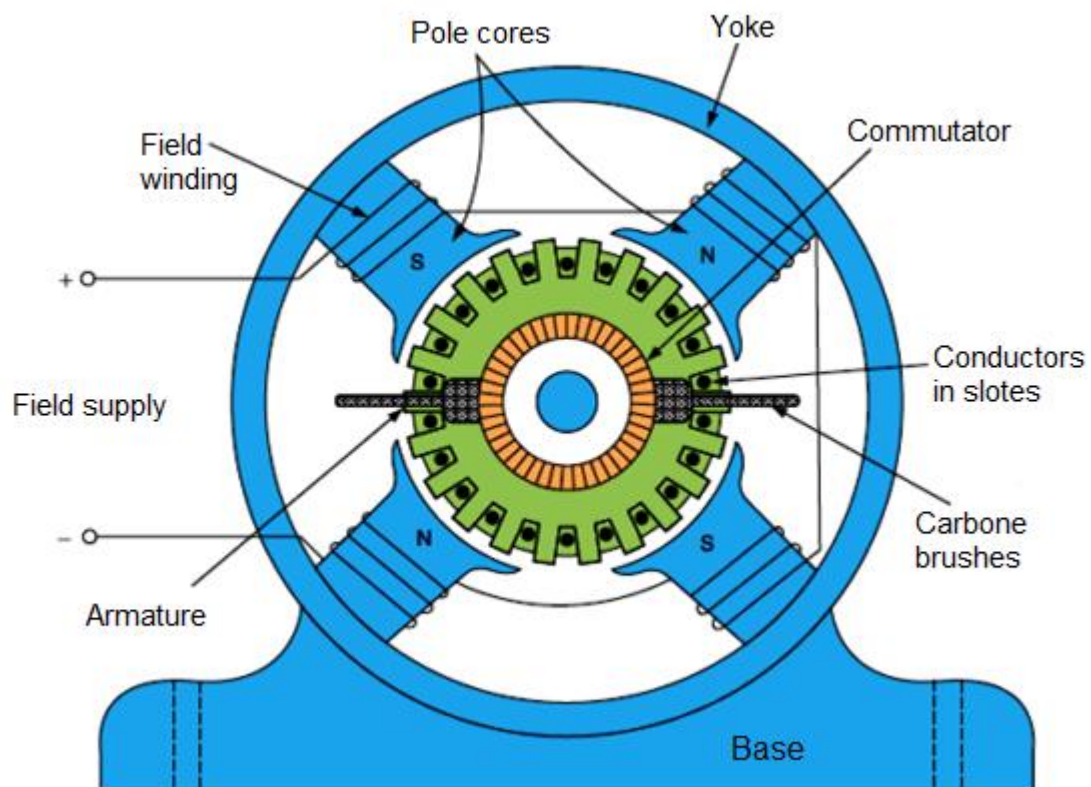


Fig.8.4 DC machine construction

Types of DC motors: There are several types of dc motors:

1. Separately Excited motor
2. Shunt DC Motor
3. Series motor
4. Compound motor

The circuit connection diagrams of these four types of dc motors are shown in Fig.8.5.

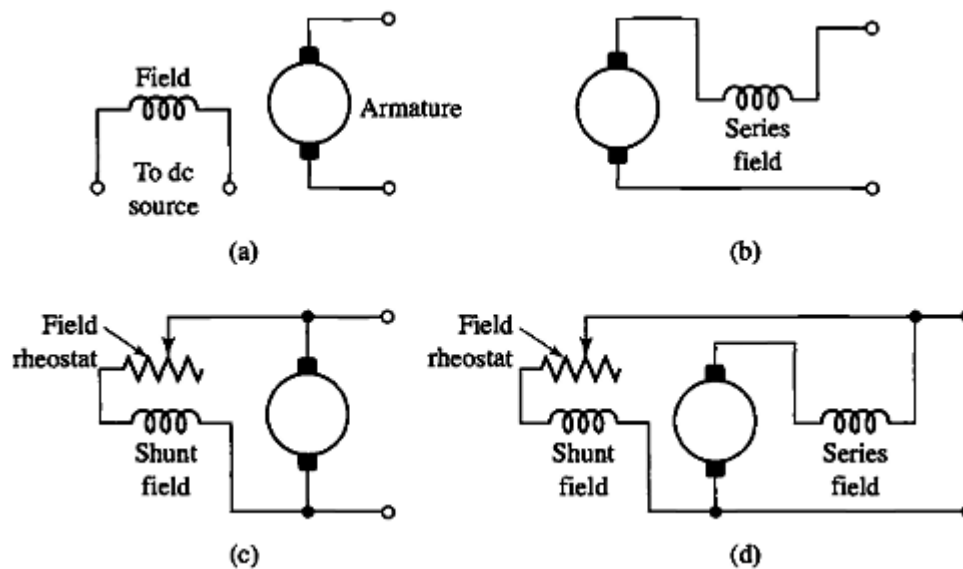


Fig.8.5.Connection of the field circuit and armature circuit for (a) separately excited motor,(b) series motor (c) shunt motor and (d) compound motor.

In this lecture we shall consider mainly the separately excited and the shunt DC motors.

3.1 Separately Excited and Shunt DC Motors

A separately excited dc motor is a motor whose field circuit is supplied from a separate constant-voltage power supply, while a shunt dc motor is a motor whose field circuit gets its power directly across the armature terminals of the motor.

When the supply voltage to a motor is assumed constant, there is no practical difference in behaviour between these two machines. Unless otherwise specified, whenever the behaviour of a shunt motor is described, the separately excited motor is included too.

The equivalent circuits of these two DC motors are shown in Fig.8.6

The KVL equation for the armature circuit is:

$$V_T = E_A + I_A R_A$$

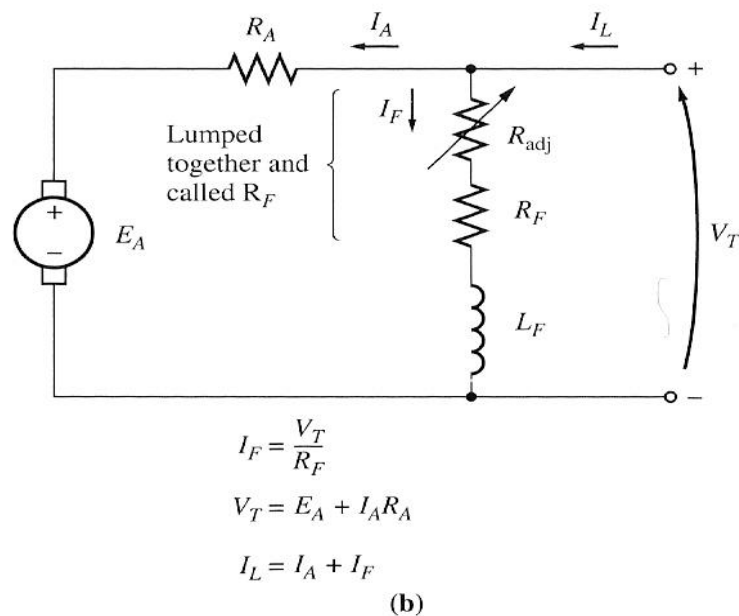
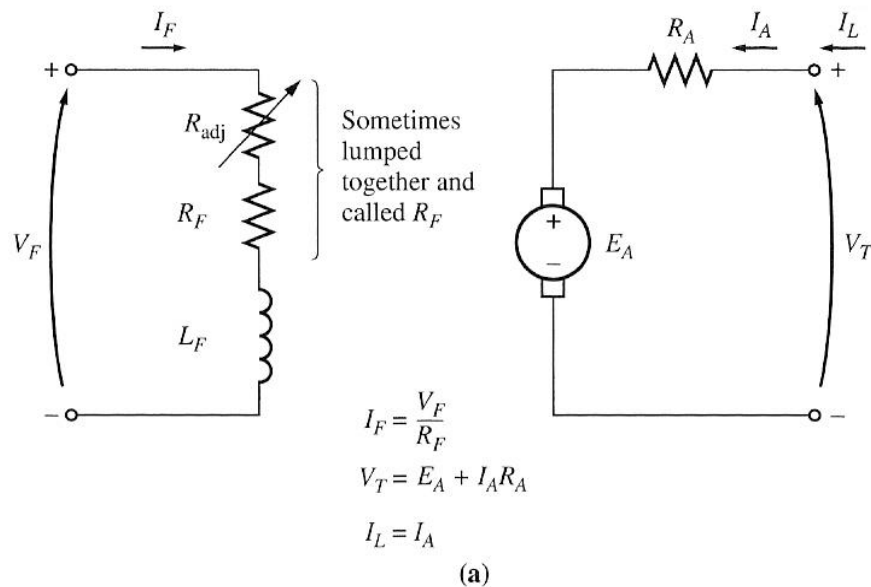


Fig.8.6 The equivalent circuit of (a) separately excited dc motor and (b) shunt dc motor.

The internal generated voltage (back emf) is given by:

$$E_A = K_e \phi n$$

Where n = speed of the motor in revolution per minute (rpm),

Φ = flux per pole in Weber (Wb),

K_e = Machine constant = $p.Z / 60a$

p = number of poles, Z =total number of conductors , a = number of parallel paths ($a=p$ for lap winding , $a= 2$ for wave winding).

and the developed motor torque is

$$T_d = K_T I_A \phi$$

K_T = Torque constant = $9.55 K_e$, I_A = armature current (A).

The speed equation and the terminal characteristics of a DC Motor

A terminal characteristic of a dc machine is a plot of its output torque versus speed.

The output characteristic of a separately excited and shunt dc motors are approximately the same and can be derived from the induced voltage and torque equations of the motor plus the KVL as follows:

$$\text{KVL} \rightarrow V_T = E_A + I_A R_A$$

The induced voltage $E_A = K_e \phi n$

$$V_T = K_e \phi n + I_A R_A$$

Since $T_d = K_T I_A \phi$

current I_A can be expressed as: $I_A = \frac{T_d}{\phi K_T}$

Combining the V_T and I_A equations:

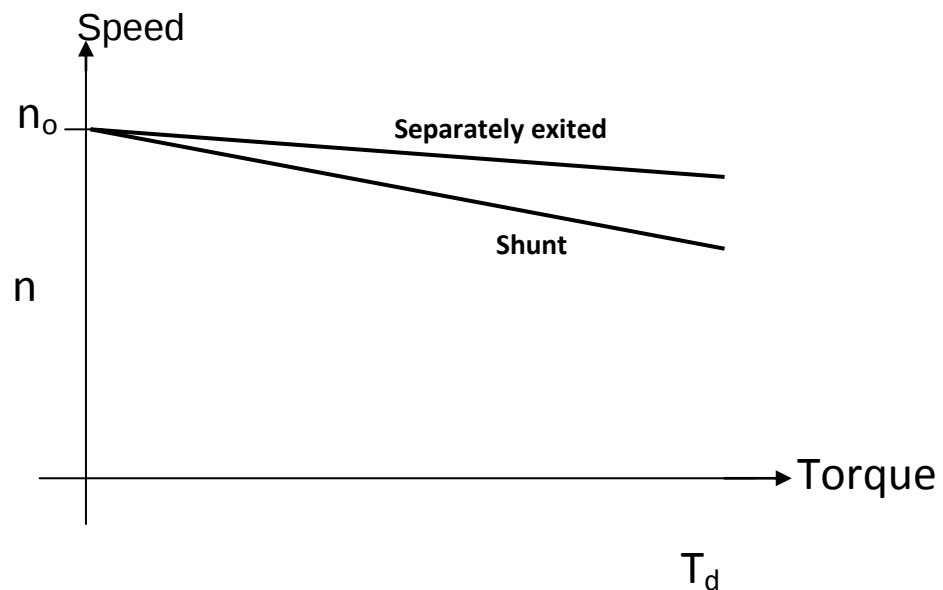
$$V_T = K_e \phi n + \frac{T_d}{K_T \phi} R_A$$

Finally, solving for the motor's speed:

$$n = \frac{V_T}{K_e \phi} - \frac{R_A}{K_T K_e \phi^2} T_d$$

Where n = speed in rpm.

This equation is called the dc motor speed equation and is just a straight line with a negative slope. The resulting torque-speed characteristic of a shunt dc motor is shown in fig.8.7:



Fig, 8.7 Speed - torque characteristic of a shunt or separately excited dc motor.

Where : n_0 = no load speed (i.e. when $T_d = 0$) or

$$n_0 = \frac{V_T}{K_e \phi}$$

Speed Control of Shunt and separately excited DC Motors

Two common methods

- i - Adjusting the field resistance R_F (and thus the field flux ϕ)
- ii Adjusting the terminal voltage applied to the armature.

Less common method:

- lii-Inserting a resistor in series with the armature circuit.

In this lecture we shall consider mainly the DC motors speed control using armature voltage control by AC-to-DC converters. These single-phase and three-phase converters (drives) are shown in Figs 8.8 and 8.9 respectively.

Types of DC Drives

1. Single-phase DC Drives

Type	Circuit	Operation
half-wave 1 pulse		 Below $\frac{1}{2}$ hp
semi-converter 2 pulse		 Up to 20 hp
full converter 2 pulse		 Up to 20 hp
double converter 2 pulse		 Up to 20 hp

Fig.8.8

2. Three-phase DC Drives

Type	Circuit	Operation
half-wave 3 pulse		 10-50 hp
semi-converter 3 pulse		 15-150 hp
full converter 6 pulse		 100-150 hp
double converter 6 pulse		 100-2000 hp

Fig.8.9

Example 1: A separately excited DC motor has the following parameters:

$$R_a = 3 \, \Omega, \quad K_e = 0.52 \, \text{V/rpm.Wb}, \quad \Phi \text{ (flux per pole)} = 150 \, \text{mWb}.$$

The motor speed is controlled by a full wave bridge rectifier. The firing angle α is set at 60° , and the average speed is 1250 rpm. The applied a.c. voltage to the bridge is 230 V at 50 Hz. Assuming the motor current is continuous; calculate the armature current drawn by the motor and the steady-state torque for the cases of:

(a) Fully- controlled bridge

(b) Half-controlled (semiconverter) bridge.

Solution :

(a) For fully- controlled bridge with continuous current operating mode:

$$V_{dc} = \frac{2 V_m}{\pi} \cos \alpha$$

$$V_m = \sqrt{2} \times 230 = 325.2 \text{ V}$$

$$V_{dc} = \frac{2 \times 325.2}{\pi} \cos 60$$

$$V_{dc} = 104.4 \text{ V}$$

$$E_b = K_e \phi n = 0.52 \times 150 \times 10^{-3} \times 1250$$

$$= 97.5 \text{ V}$$

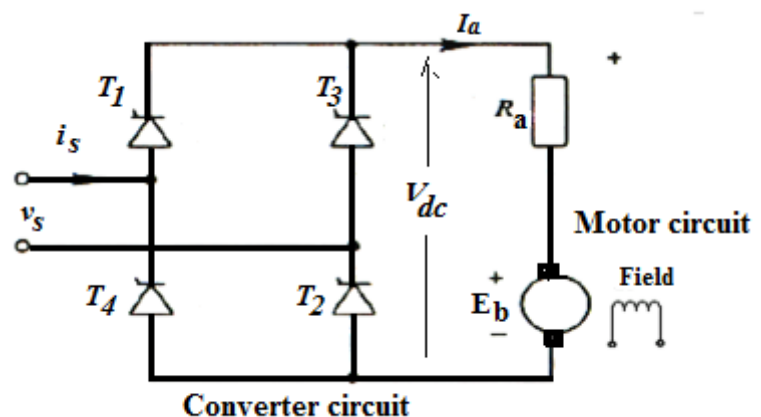
$$V_T = V_{dc} = E_a + I_a R_a$$

$$\text{Or} \quad I_a = \frac{V_{dc} - E_b}{R_a} = \frac{104.4 - 97.5}{0.3} = 23 \text{ A}$$

$$\text{Since } T_d = K_T I_a \phi$$

$$K_T = \text{Torque constant} = 9.55 K_e = 9.55 \times 0.52 = 4.96$$

$$T_d = 4.96 \times 23 \times 150 \times 10^{-3} = 17.1 \text{ N}$$



(b) For half-controlled (semiconverter) bridge.

$$V_{dc} = \frac{V_m}{\pi} (1 + \cos\alpha)$$

$$V_{dc} = \frac{325.2}{\pi} (1 + \cos 60)$$

$$V_{dc} = 155.3 \text{ V}$$

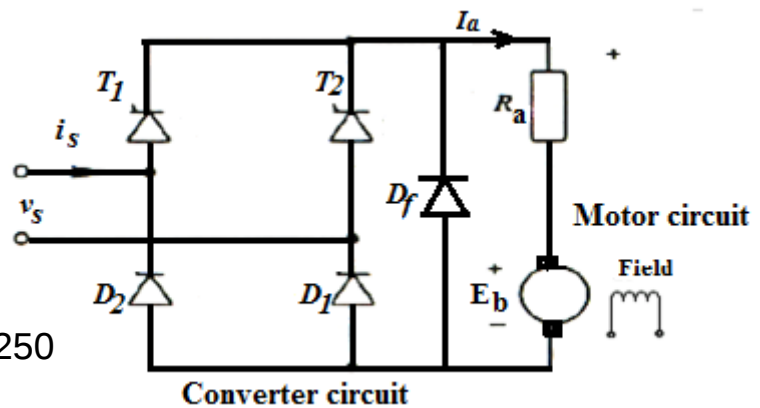
$$E_b = K_e \phi n = 0.52 \times 150 \times 10^{-3} \times 1250$$

$$= 97.5 \text{ V}$$

$$V_T = V_{dc} = E_a + I_a R_a$$

$$I_a = \frac{V_{dc} - E_b}{R_a} = \frac{155.3 - 97.5}{0.3} = 192.8 \text{ A}$$

$$T_d = 4.96 \times 192.8 \times 150 \times 10^{-3} = 146.4 \text{ N}$$

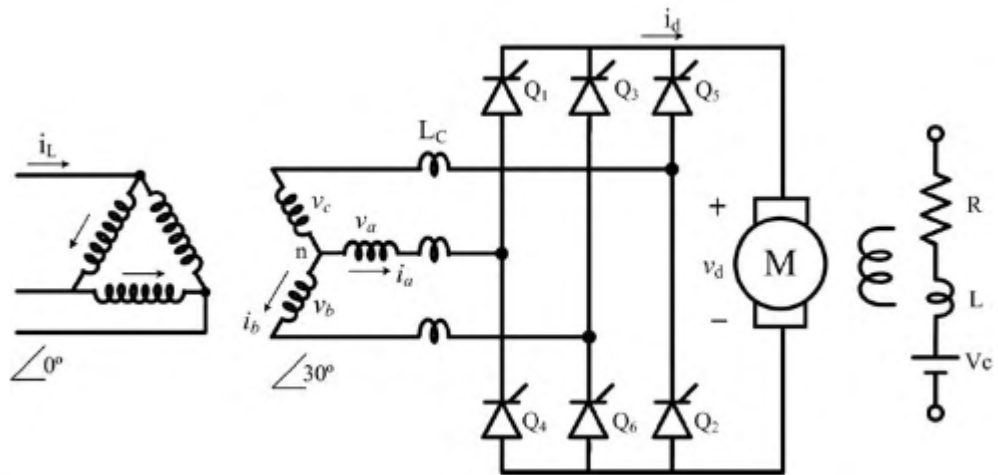


Example 2 : A three-phase full converter , shown in Fig.8.10 , is used to control the speed of a separately excited d.c. motor rated at 100 kW, 600V, 2000 rpm. The converter is connected to a 3 – phase 400 V, 50 Hz supply. The armature resistance is $R_a = 0.051 \text{ ohm}$ and the armature circuit inductance is $L_a = 10 \text{ mH}$. The motor voltage constant is $K_e \Phi = 0.25 \text{ V/rpm}$. The rated armature current is 100A and the no load current is 10A.

With the converter operates as a rectifier, and assuming that the motor current is continuous and ripple-free, determine:

- The no load speed when the firing angles: $\alpha = 0^\circ$ and $\alpha = 60^\circ$.
- The firing angle to obtain the rated speed of 2000 rpm at rated motor current.

Fig.8.10



Solution:

(a) No load condition

$$V_m = \frac{400}{\sqrt{3}} \times \sqrt{2} = 325.22 \text{ V}$$

The converter output voltage = V_{dc} = armature voltage V_T

$$V_{dc} = V_T = \frac{3\sqrt{3}}{\pi} V_m \cos \alpha$$

$$V_T = \frac{3\sqrt{3}}{\pi} \times 325.22 \cos \alpha$$

$$V_T = 538 \cos \alpha$$

For $\alpha = 0^\circ$

$$V_T = 538 \text{ V}$$

$$E_A = V_T - I_A R_A = 538 - 10 \times 0.051 = 537.5 \text{ V}$$

No load speed :

$$\text{since } E_A = K_e \phi n$$

Hence

$$n_o = \frac{E_A}{K_e \phi} = \frac{537.5}{0.25} = 2145 \text{ rpm}$$

For $\alpha = 60^\circ$

$$V_T = 538 \cos 60^\circ = 269 \text{ V}$$

$$E_A = V_T - I_A R_A = 269 - 10 \times 0.051 = 268.4 \text{ V}$$

$$n_o = \frac{E_A}{K_e \phi} = \frac{268.41}{0.25} = 1073.64 \text{ rpm}$$

(b) At full load condition

$$E_A = K_e \phi n = 0.25 \times 2000 = 500 \text{ V}$$

$$\begin{aligned} V_T &= E_A + I_A R_A = 500 + 100 \times 0.051 \\ &= 505 \text{ V} \end{aligned}$$

$$505 = 538 \cos \alpha$$

$$\text{Hence } \alpha = 20.14^\circ$$

Dual converters

The dual converter consists of two AC-to-DC converters connected in anti-parallel as shown in Fig. 8.11. If converter 1 operates, and it gives a positive output dc voltage ($+V_{dc}$). However if converter 2 operates it gives negative dc voltage $-V_{dc}$. It is important to be noted that, the two converters must not operate simultaneously to avoid short - circuiting of the two converters.

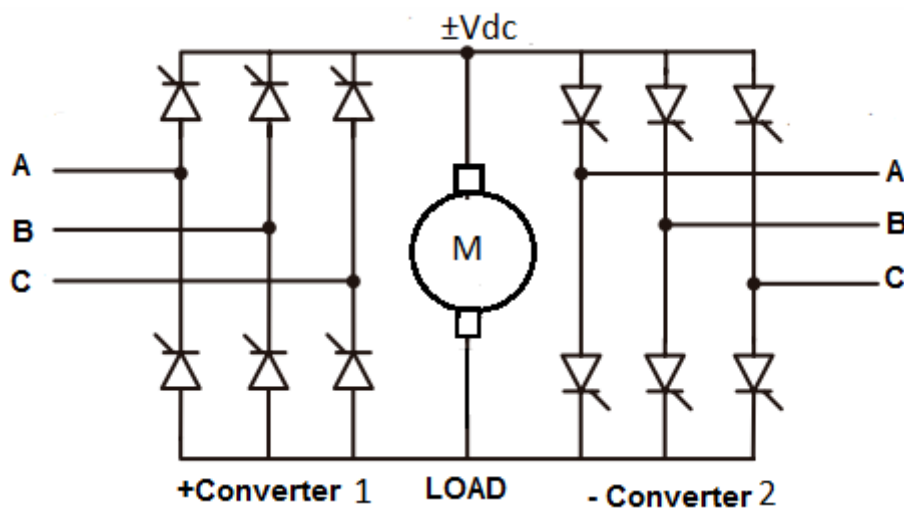


Fig.8.11

The dual converter provides the facility of operation in four quadrants (Fig.8.12). If the load is a dc motor, the motor can run in four modes of operation as indicated in Fig.8.13.

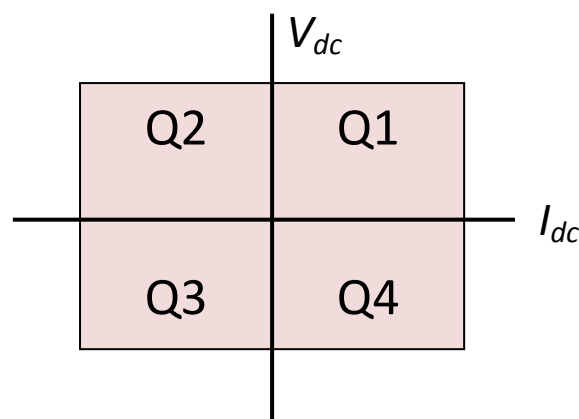


Fig.8.12

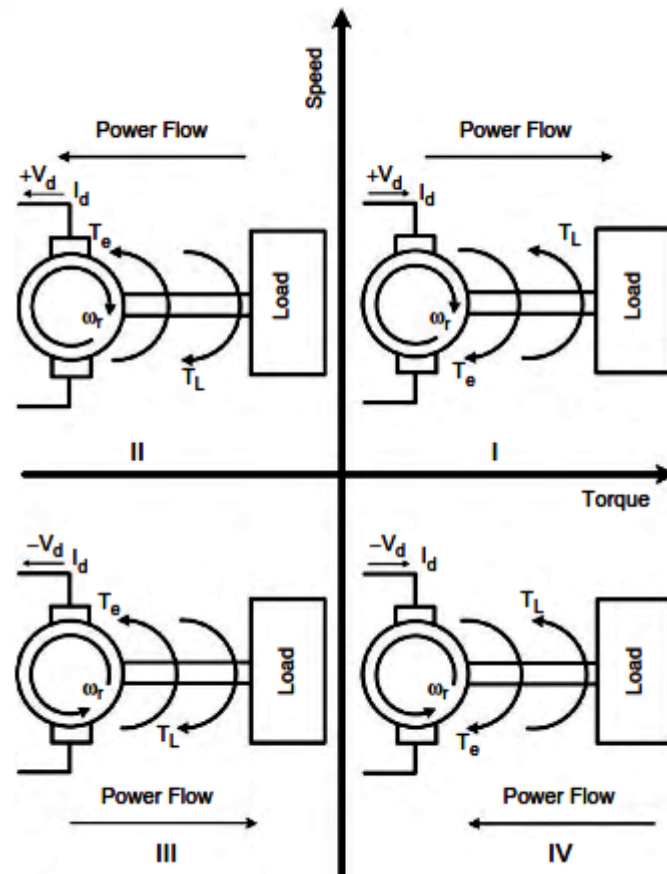


Fig.8.13