Module

7

Electrical Machine Drives

Lesson
33

Electrical Actuators: DC Motor Drives

Instructional Objectives

After learning the lesson students should be able to

A. Describe the major constructional features of dc motors
B. Explain the principle of torque generation
C. Derive the dynamic speed response characteristics relating armature voltage, load torque and speed
D. Describe the realization of a variable voltage controlled source using switch mode power converters.
E. Draw the block diagram a typical speed control loop for a separately excited dc motor.

Introduction

Motion control and drives are very important actuation subsystems for Process and Discrete Manufacturing Industries. As we have already seen in Lessons 23, 24 and 31, motion control systems are critical for product quality in discrete manufacturing, while variable speed drives lead to significant energy savings in common industrial loads such as pumps, compressors and fans.

Variable speed drives can be categorized into Adjustable Speed Drives and Servo Drives. In adjustable speed drives the speed set points are changed relatively infrequently, in response to changes in process operating pints. Therefore transient response of the drive system is not of consequence. In servo drives, as in CNC machines, set points change constantly (as in contouring systems).

While ac motors have replaced dc motors in most of the adjustable speed drive applications. For servo drive applications, dc motors are still used, although they are also being replaced by BLDC motors. In this lesson we discuss speed and position control with dc motors. The next lesson discusses adjustable speed drives using induction motors, while Lesson 35 discusses BLDC servo drives.

DC Servomotors

Direct current servomotors are used as feed actuators in many machine tool industries. These motors are generally of the permanent magnet (PM) type in which the stator magnetic flux remains essentially constant at all levels of the armature current and the speed-torque relationship is linear.

Direct current servomotors have a high peak torque for quick accelerations. A cross-sectional view of a typical permanent magnet dc servomotor is shown in Fig. 33.1.

Mechanical Construction

Stator consists of Yoke and Poles and provides mechanical support to the machine. The yoke provides a highly permeable path for magnetic flux. It is made of cast steel. Field poles are made of thin laminations stacked together. This is done to minimize the magnetic losses due to the armature flux. The cross sectional area of the field pole is less than that of the pole shoe. The pole shoe helps to establish a uniform flux density around the air gap.

Field winding: DC excitations are provided to field windings wound on pole shoes to create electromagnetic poles of alternating polarity. Depending on the connections of field windings DC motors may be termed as shunt, series, compound or separately excited. Shunt motors have field winding connected in parallel with the armature winding while series motors have the field winding connected in series with the armature winding. A compound dc machine may have both field windings wound on the same pole. Smaller DC servomotors generally have permanent magnets for poles.

Armature – The rotating part of a dc machine is called the armature. The length of the armature is usually the same as that of the pole. It is made of thin, highly permeable, and electrically insulated circular steel laminations that are stacked together and rigidly mounted on the shaft. The laminations have axial slots on their periphery to house the armature coils. Insulated copper wires are typically used for the armature coils to achieve a low armature resistance.

Commutator – The commutator is made of wedge – shaped hard-drawn copper segments. Sheets of mica insulate the copper segments from one another. One end of the armature coil is electrically connected to a copper segment of the commutator. The commutators rotate with the armature keeping a sliding contact with the brushes, which remain stationary.

Brushes: Brushes are held in a fixed position by means of brush holders and remain in sliding contact with the commutator segments. An adjustable spring inside the brush holder exerts a constant pressure on the brush in order to maintain a proper contact between the brush and the commutator. The brushes are connected to the armature terminals of the machine. The material for the brush is normally carbon or carbon-graphite.

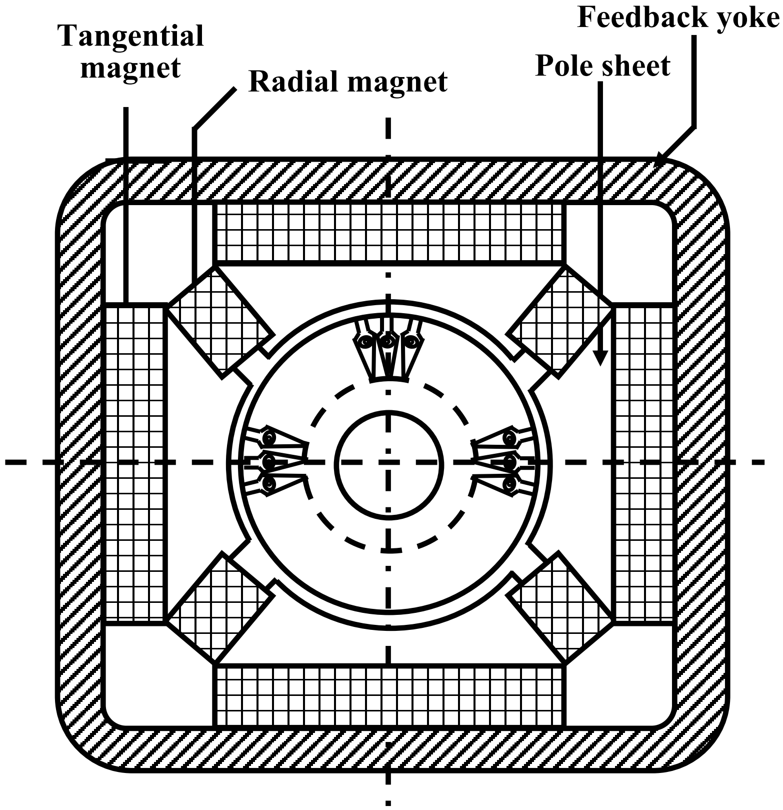


Fig. 33.1 Cross-section of a permanent magnet-excited dc servomotor.

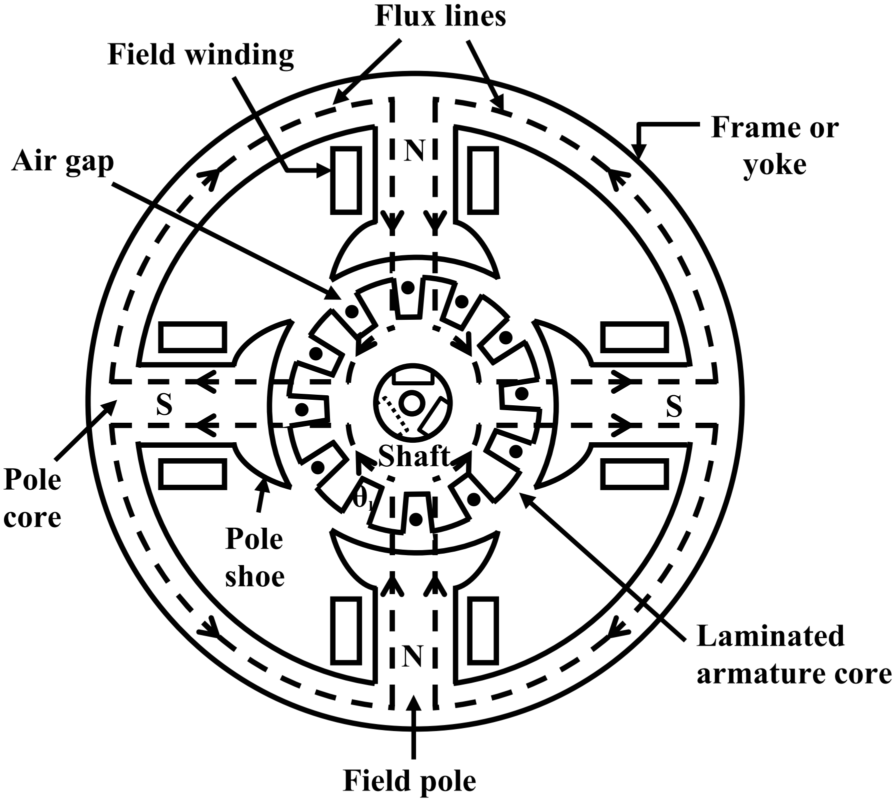


Fig. 33.2 Diagrammatic sketch of a D.C. machine.

Principle of Operation

The cross-sectional view of a DC motor has been shown in Fig. 33.2. Consider a particular position in space between stator and rotor. Whichever conductor is present there, will have current flowing through it, which depends on the applied armature voltage. This current would produce a flux which would interact with the field flux to produce torque. In course of rotation of the armature adjacent conductors will occupy this position in space. No matter which conductor comes to that particular position at any given point of time, it will have same current flowing through it. This is true for all the positions although the magnitude and polarity of the torque produced by individual conductors in different positions may be different. The polarity of the torque is identical for conductor positions under north or south pole, since the direction of the current flowing through it at that position is unique, given the direction of rotation and the applied armature voltage due to the commutators slipping over the brushes, as shown in Fig. 33.3.

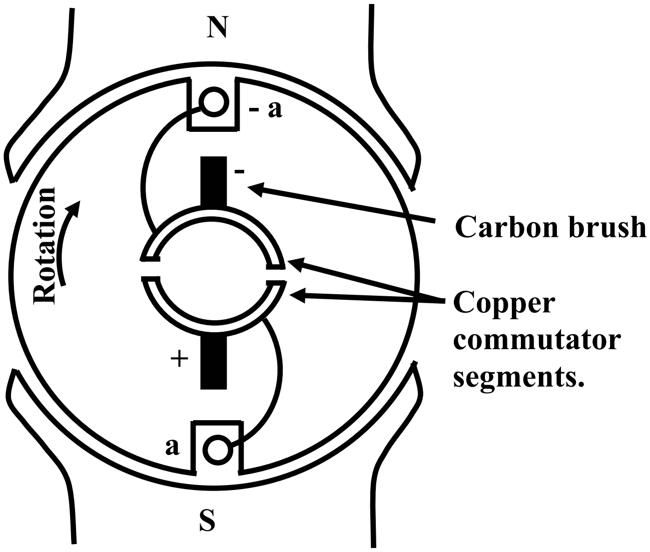


Fig. 33.3 Brush and commutator positions in a DC motor

Points to Ponder: 1

A. *Why is it that dc motors are preferred for control applications, such as actuation, but ac motors are preferred for high power applications, such as compressors and fans ?*

B. *In a dc motor, is the field flux stationary or rotating? Is the armature flux stationary or rotating?*

To quantify the net torque produced,

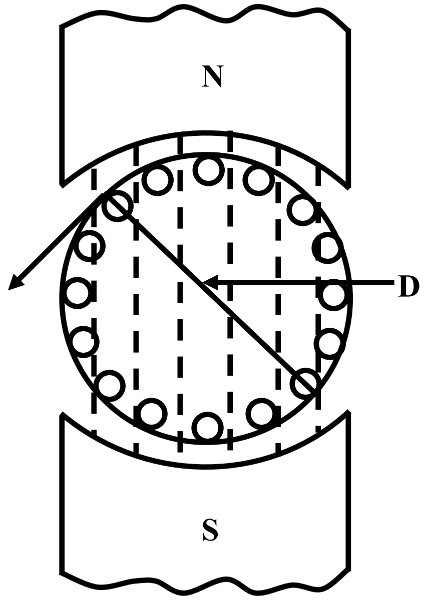


Fig. 33.4 Principle of rotation.

let Φ be the flux per pole and pole pitch be $Y = \frac{\pi D}{2p}$ where D is the diameter of the armature and p be number of pole pairs. Let L be the length of the pole = length of the conductor, then pole area = $YL = \frac{\pi D}{2p}L$

$\therefore$ Flux density $B = \Phi/(YL) = \frac{\Phi}{\frac{\pi D}{2p}L} = \frac{2p\Phi}{\pi DL}$.

Force (f) experienced by an armature conductor carrying current $I_c = B.I_c.L$: Therefore, torque experienced by the conductor = $B\ I_c\ L\frac{D}{2} = \frac{2p\Phi}{\pi DL}.I_c.L.\frac{D}{2} = \frac{1}{\pi}I_c.p.\Phi$.

The principle has been demonstrated in Fig. 33.4. If the armature current is Ia, then conductor current $I_c = \frac{I_a}{c}$ where c is the number of parallel paths. If z be the total number of conductors, then total torque developed $T = \frac{1}{\pi}.\frac{I_a}{c}.z.p.\Phi$ Nm, if Ia is in Ampere and Φ is in Wb.

$$T = \frac{1}{\pi}\frac{I_a}{c}.z.p.\Phi = 0.318\frac{I_a}{c}zp\Phi \quad \text{Nm.}$$

One can therefore see that the torque produced is proportional to the armature current, if the flux can be assumed to be constant.

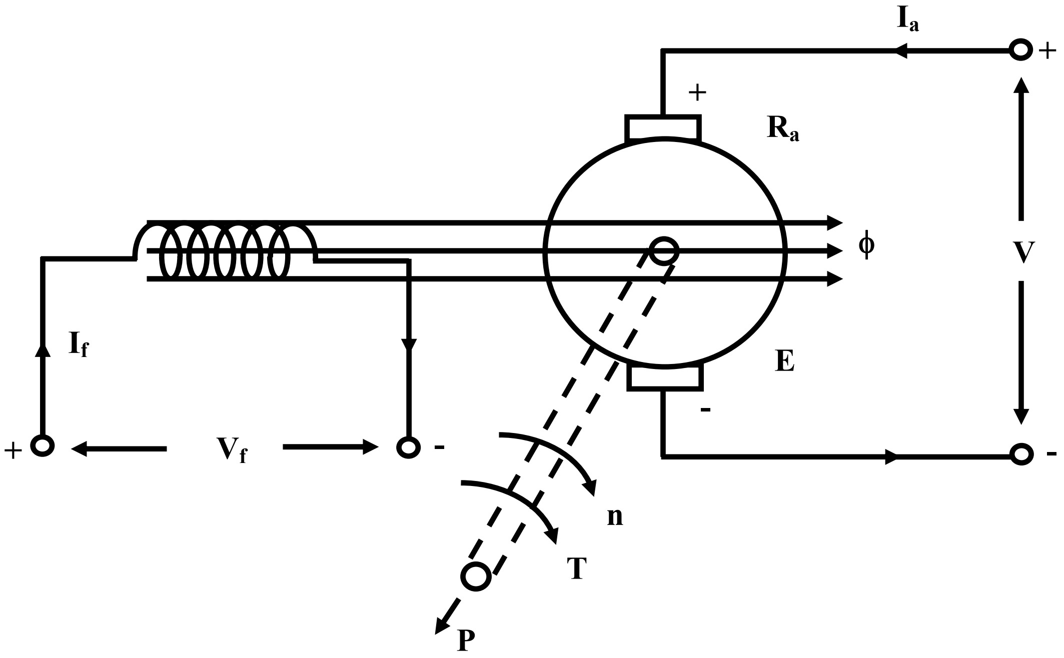


Fig. 33.5 Schematic of a separately excited DC motor

Two equations are required to define the behavior of a dc machine: the torque and the voltage equations. Fig. 33.5 describes a schematic of a separately excited DC motor. Where T = *magnetic* torque, N.m

ϕ = flux per pole, Wb
$/_a$ = current in armature circuit, A
E = induced voltage (emf), V
ϕ = angular velocity, rad/s
K_f = constant determined by design of winding
I_f = Field current
n = speed of the motor in rpm
V_f = field voltage
P = mechanical power

The torque equation relates the torque, to the armature current:

$$T = K_f \phi I_a \tag{33.1}$$

and the voltage equation relates the induced voltage in the armature winding to the rotational speed:

$$E = K_f \phi \omega \tag{33.2}$$

For a motor, an input voltage V is supplied to the armature, and the corresponding voltage equation becomes

$$E = V - I_a R_a = K_f \phi \omega \tag{33.3}$$

where R_a is the resistance of the armature circuit and $I_a R_a$ is the voltage drop across this resistance. The armature inductance is negligible in Eq.(33.1). Equation 33.3 multiplied by Armature current I_a, yields the power equation,

$$P = \omega T = V I_a - I_a^2 R_a \tag{33.4}$$

where P is the mechanical output power, VI_a is the electrical input power, and $I_a^2 R_a$ is the electrical power loss.

$$T = K_t I_a \qquad (33.5)$$

$$V - I_a R_a = K_v \omega \qquad (33.6)$$

The parameters K_t and K_v are referred to as the torque and voltage constants. In SI units the torque constant in Newton-meters per ampere equals the voltage constant in volt-seconds per radian.

Zones of steady state torque-speed characteristics of the motor are shown in Fig. 33.6. Note that constant torque characteristics can be maintained by armature voltage control up to a certain speed. At the rated speed this would require rated voltage to be applied to the armature voltage, and further increase would not be possible due to limitations of the motor such as insulation ratings and thermal ratings. Speed increase beyond this point would only be possible at the cost of a reduction in torque and the machine will operate in the constant power mode. The corresponding power characteristics are shown in dotted lines.

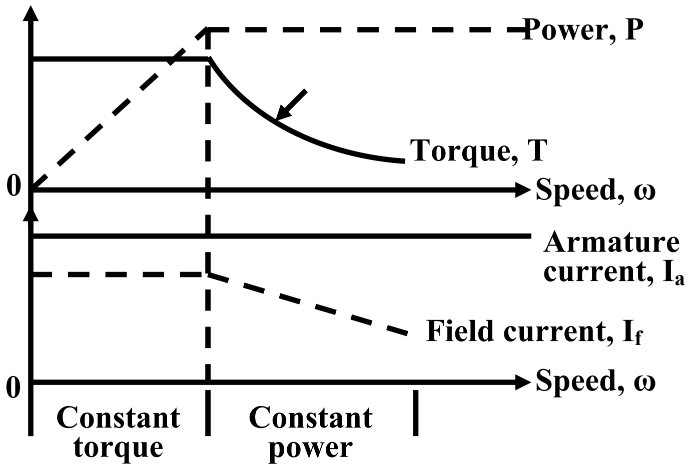


Fig. 33.6 Speed, torque and power characteristics of separately excited DC motors

Modern dc motors often use a permanent-magnet (PM) field, rather than an externally excited field. Both types are referred to as dc servomotors and are characterized by Eqs. (33.5) and (33.6). The PM obviates the need for a field voltage source and results in higher efficiency and fewer thermal problems.

The dc servomotor drives a mechanical load consisting of dynamic and static components:

$$T = J\frac{d\omega}{dt} + T_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33.7)$$

Where J is the combined moment of inertia of the motor and load, and T_s is the static load due to friction and cutting forces in NC systems.

Elimination of I_a and T from Eqs. (33.5) through (33.7), and rearrangement of the terms so as to separate the independent variables, gives the speed equation

$$\tau_m \frac{d\omega}{dt} + \omega = \frac{1}{K_v}V - \frac{R_a}{K_t K_v}T_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33.8)$$

where τ_m is the mechanical time constant of the loaded motor and is defined by

$$\tau_m = \frac{JR_a}{K_t K_v} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33.9)$$

The Laplace transform of Eq. (33.8) is

$$\omega(s)=\frac{K_mV(s)-(R_aK_m/K_t)T_s(s)}{1+s\tau_m}\ \ldots\ldots\ldots\ldots\ldots\ldots..(33.10)$$

where K_m is the gain of the motor and is defined by $K_m = 1/K_V$.

Points to Ponder: 2

A. *Can you identify some of the assumptions that have been made in the derivation of the above model?*

B. *What can you say about the input-output transfer function of the dc motor?*

Braking methods in servo-drive

Braking of a motor is a normal requirement of many industrial applications, such as CNC machines to stop the slide/spindle to the programmed position or within a definite distance in case of power failure or emergency conditions. There are two types of braking employed in servo-drives.

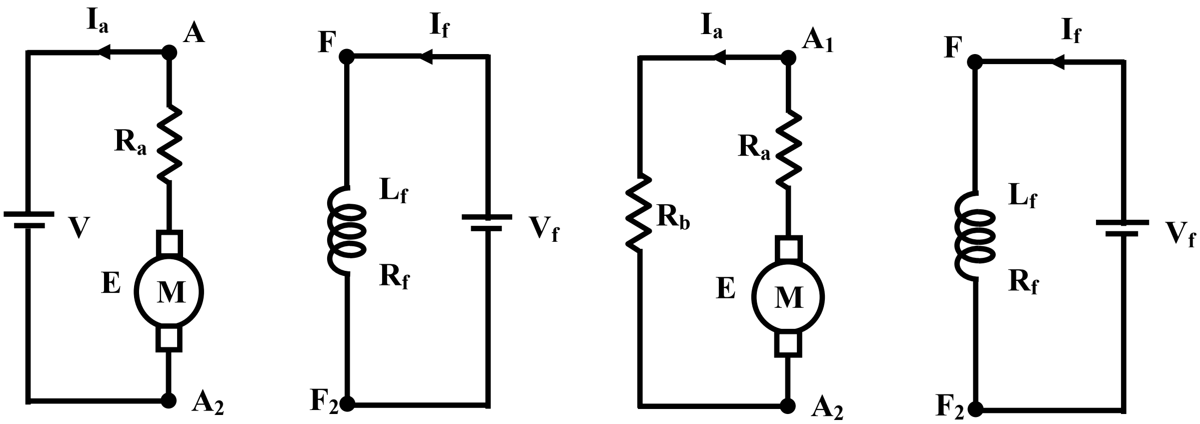


Fig. 33.7 (a) Regenerative braking (b) Dynamic braking

Dynamic braking (Fig. 33.7(b)) Braking is realized by shorting the armature leads through contactor and dissipating the kinetic energy stored in the motor into the Dynamic Braking Resistor (DBR) in the form of heat. During this period, reverse torque will be generated which will bring the motor to a stand still faster. This type of braking is a fail safe braking and finds application particularly during mains failure and emergency situations.

Regenerative braking (Fig. 33.7(a)): Regenerative braking is possible if the motor is driven by the stored mechanical energy of the load and energy is returned to the source, i.e., dc link or the mains. The feeding of power back to dc source raises the dc link voltage. Depending on the load conditions and speed, this can reach dangerous levels unless the additional energy is returned to ac mains by using the converter in the inverter mode. Thus, regenerative braking is possible only with fully controlled drives.

Transistor PWM dc Converter

Transistor dc drives are ideal for controlling dc servomotors. The transistors are commonly used in the switching mode at frequencies between 1 kHz and 10 kHz (pulse width modulated). In the PWM technique the average dc voltage is proportional to the pulse width.

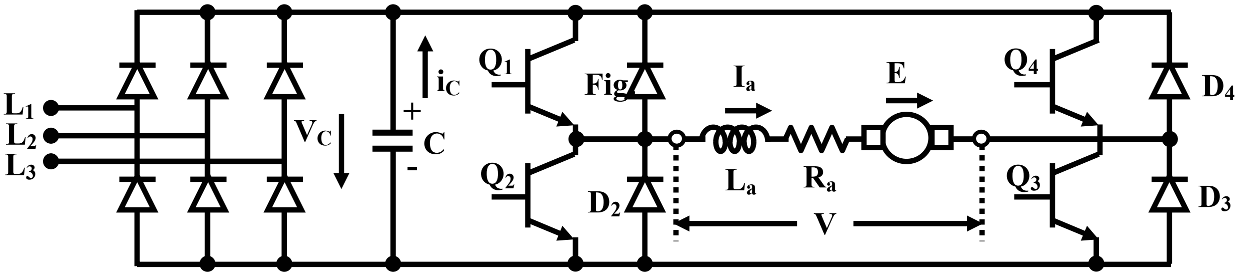


Fig. 33.8 Transistor dc four quadrant amplifier.

Figure 33.9 shows the four-quadrant operation of a dc drive. Four-quadrant operation of a drive is enables it for:

(a) Forward running—quadrant I
(b) Reverse running—quadrant III
(c) Forward braking—quadrant II
(d) Reverse braking—quadrant IV

Fig. 33.8 shows the basic diagram of a transistor dc four-quadrant amplifier. A rectifier is fed from the three phase ac line and delivers power into a dc bus. The buffer capacitor *C* can supply stored energy for acceleration and can accept energy as long as the motor absorbs mechanical energy during braking. The buffer capacitor is thus working as generator and supplies electrical energy. The capacitor is so chosen that the dc bus voltage changes only slightly. The motor can be controlled selectively for clockwise or counterclockwise rotation and can be accelerated or braked by controlling two diagonally opposite transistors (Q_1 - Q_3 or Q_2 - Q_4). The magnitude of the armature voltage V and thus the speed *n* is determined by pulse width modulation of transistors acting as switches for a switched transistor chopper. Two energy storages are necessary to operate a transistor controller in all four quadrants:

- a large capacitor C which maintain the voltage V_C constant and is capable of accepting energy to store and to deliver.
- an inductance, which smoothens the motor current and acts as an energy storage element. This is especially important during braking mode. At high switching frequencies of the drive, the armature inductance L_a of the motor is generally sufficient.

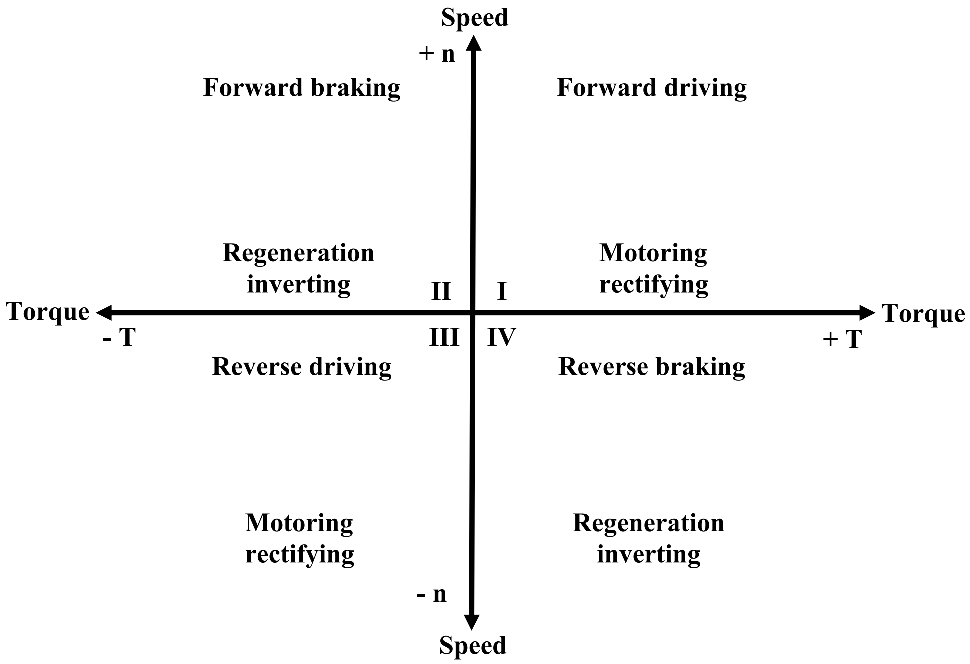


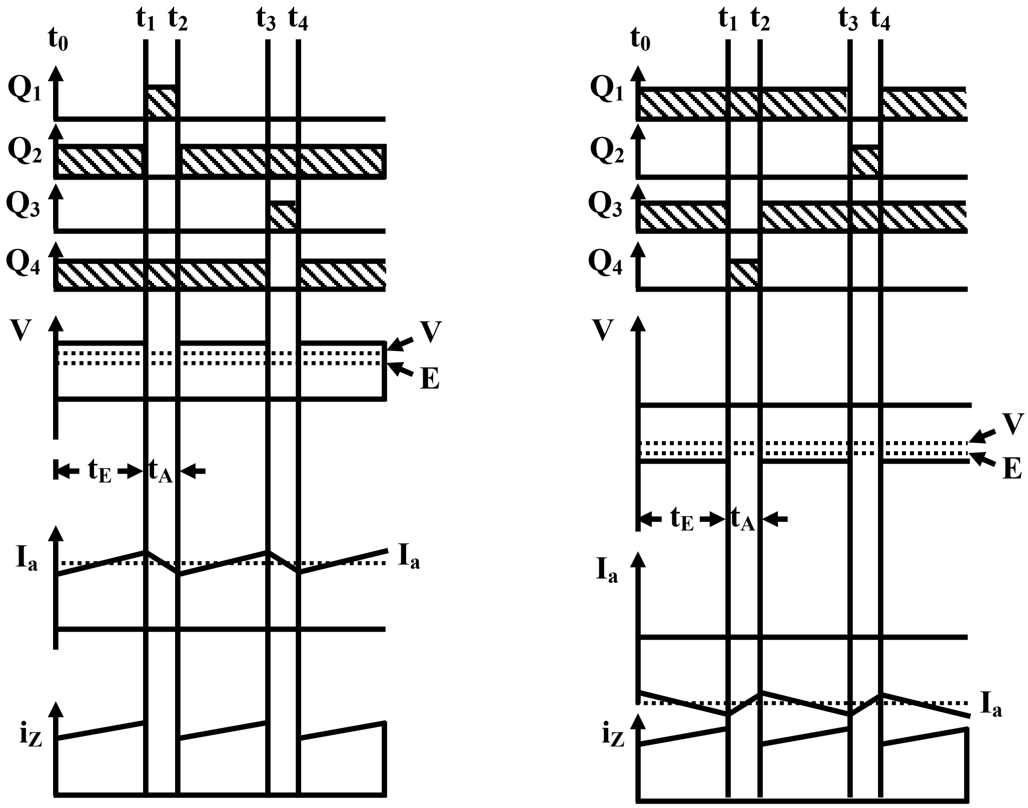
Fig. 33.9 Four-quadrant operation of a dc drive

Driving, clockwise (CW), I quadrant

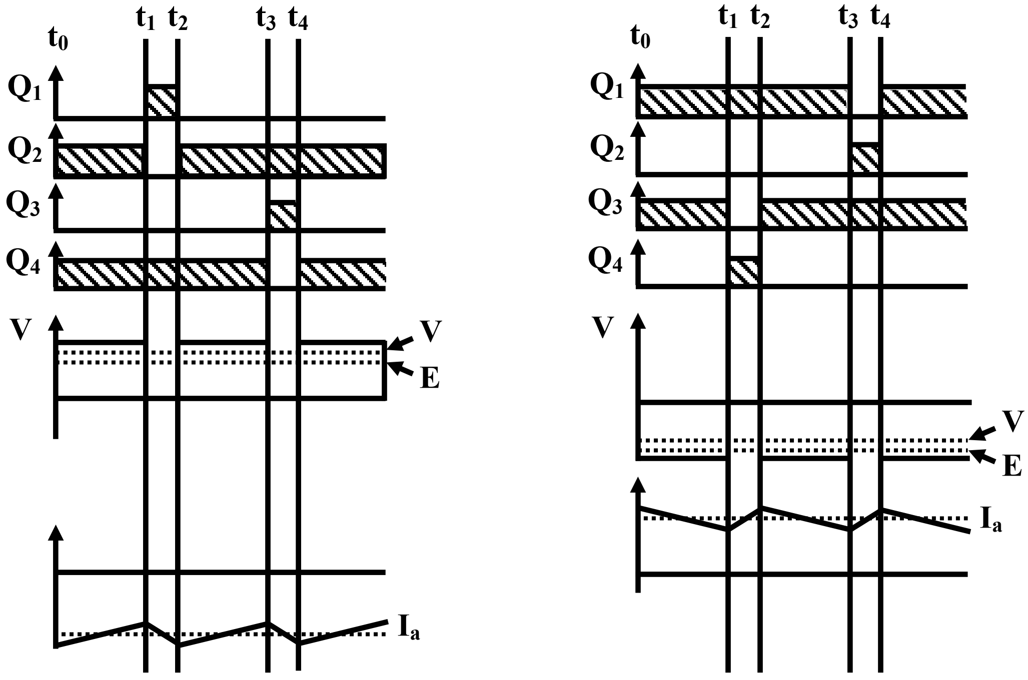
The voltage and the current waveforms for this mode are shown in Fig. 33.10. Assume that Logic ‘0’ represents that a transistor is ON. The following sequence of phases occurs.

- From the figure, at the time t_0, both transistors Q_1 and Q_3 are ‘ON’. The armature voltage of the motor is positive, i.e., $V = V_C$ and current flows through the motor via Q_1, L_a, R_a and $Q_{3.}$
- At time t_1, switch Q_1 *is* opened. Instantaneously, due to the armature inductance, the motor current commutates from Q_1 to diode D_2, so that current through the inductance does not reverse. This current is not flowing through the dc bus any more, but is circulated by the stored energy in the armature inductance against the back emf of the motor. in the lower half of the bridge from Q_3 through D_2, L_a, R_a, motor and back to Q_3 (free wheeling), at this point the motor voltage V and the dc bus current I_a are zero.
- At time t_2, the situation is the same as it was at time $t_{1.}$ At time t_3, switch Q_3 is open. The motor current now commutes through diode D_4 and circulates in the upper half of the bridge circuit via Q_1, L_a, R_a, motor D_4 and Q_1, The motor voltage and dc link current go to zero again. At time t_4, switch Q_3 is closed and a new switching cycle begins.

The mean value of the motor voltage V depends on the ratio between the switch ‘ON’ time t_{ON} and the switch OFF time $t_{OFF.}$ During the switch ON time t_{ON} the energy is derived from the dc bus while during the period t_{OFF}, assuming the current does not go to zero, the current is driven by the energy stored in the inductance. The motor thus maintains a positive product from voltage V and current I_a during both the periods t_{ON} and t_{OFF} and thus converts electrical energy into mechanical energy. For simplicity the drop across the motor (I_a R_a) is neglected since it is small compared to the induced voltage E in the motor. Driving in the CCW direction is similar.



Driving clockwise **Driving counter-clockwise**



Braking clockwise **Braking counter-clockwise**

Fig. 33.10 Voltage and the current wave forms for Fomquadrant Drive.

Braking, clockwise, IV quadrant

For rapid braking, the torque has to reverse, while the speed reduces but the motor continues in the same direction. Thus, the mean value of the motor current I_A and the armature voltage V must have opposite signs for a back flow of actual power out of the motor circuit. For stopping the motor, the mean value of the armature voltage V is reduced compared to voltage induced in the motor E. Thus, after the magnetic energy stored in the motor inductance is exhausted, The direction of current within the motor circuit is reversed. The transition from driving to braking is the result of decrease in t_{ON} and an increase in t_{OFF}. At time $t_{l,}$ switch Q_2 is closed. The voltage E drives a current through R_a, L_a, Q_2 and D_3. The energy is stored in the L_a inductance which is given by

$$W_{LA} = \frac{1}{2} I_a L_a^2$$

where W_{LA} = energy stored
L_a = inductance and
I_a = current through the motor.

At time t_2, switch Q_2 is OFF and current Ia commutates over to diode D_l and flows into the dc bus charging the capacitor and then returns through D_3 to the motor. The voltage induced in the inductance and the induced motor voltage is in series. Their sum is larger than the voltages delivered from the dc bus. Energy is thus fed back into dc bus and stored in the capacitor as given by

$$W_C = \frac{1}{2} I_A CV_C^2$$

where W_C = energy stored
C = capacitance and
V_C = dc link voltage

Thus, the voltage of the dc link increases. If now at time t_3, the switch Q_4 is turned ON, the armature current will flow in the upper circuit through R_a, L_a, D_l and Q_4 and energy will again be stored in L_a. This energy in turn is fed into the dc bus at time t_4 via diodes D_1 and D_3. This cycle is repeated periodically.

The time period t_4 is for storing the energy in the inductance and period t_{ON} is for feeding the energy back into dc bus. The mean values of the motor current and motor voltage have opposite polarity. The motor is braked with mean constant torque because the actual power is fed back to the source. Again, the cycle of operation during CCW braking is similar.

Advantages of transistor PWM dc drives over thyristor drives

(a) PWM transistor drive has a high form factor of approximately 1.
(b) Less heating of the motor and an increased torque output (about 20% more than thyristor drives).
(c) High banwidth dynamic response resulting in better surface finish, low machining stress and no resonance problems for machine tools.
(d) Increased device reliability of the transistor.

Therefore transistor PWM amplifiers are used advantageously as servo drives for fast and accurate actuation of industrial machines.

Points to Ponder: 3

A. *Can you describe what happens in dynamic braking?*

B. *There are drives that are cheaper and permit restricted operations, such as operation only in 2 quadrants or even a single quadrant. Study the operation if the dc motor is fed from a single phase fully controlled rectifier. Compare the resource requirements of this configuration with the one presented above.*

Having presented the basic principles of armature voltage control using a controlled variable voltage source such as the PWM switching converter, below we describe the over all control loops for speed control.

Closed loop of control of DC motors

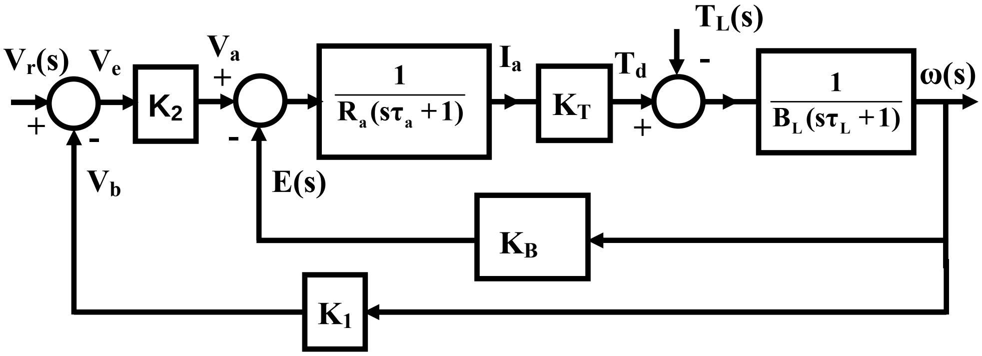


Fig. 33.11 Block diagram of closed-loop speed control of separately excited DC motor

The basic structure of the control loop is shown in Fig. 33.11. For servo drives, the speed control loop is an inner loop of the cascade structure and is generally proportional in nature. In independent speed control applications this may be designed as a PI loop also. Speed may be fed back from a tachogenerator, or derived from position measurements by differentiation. A practical implementation structure of the above control loop is shown below in Fig. 33.12. This typically includes a current control loop for torque control as well as a field voltage control loop. Note the PI speed and current control loops. Additional circuitry needed for practical implementations, such a filters for noise removal in current and speed feedback channels as well as current limiters in set points to avoid phenomena such as integrator windup.

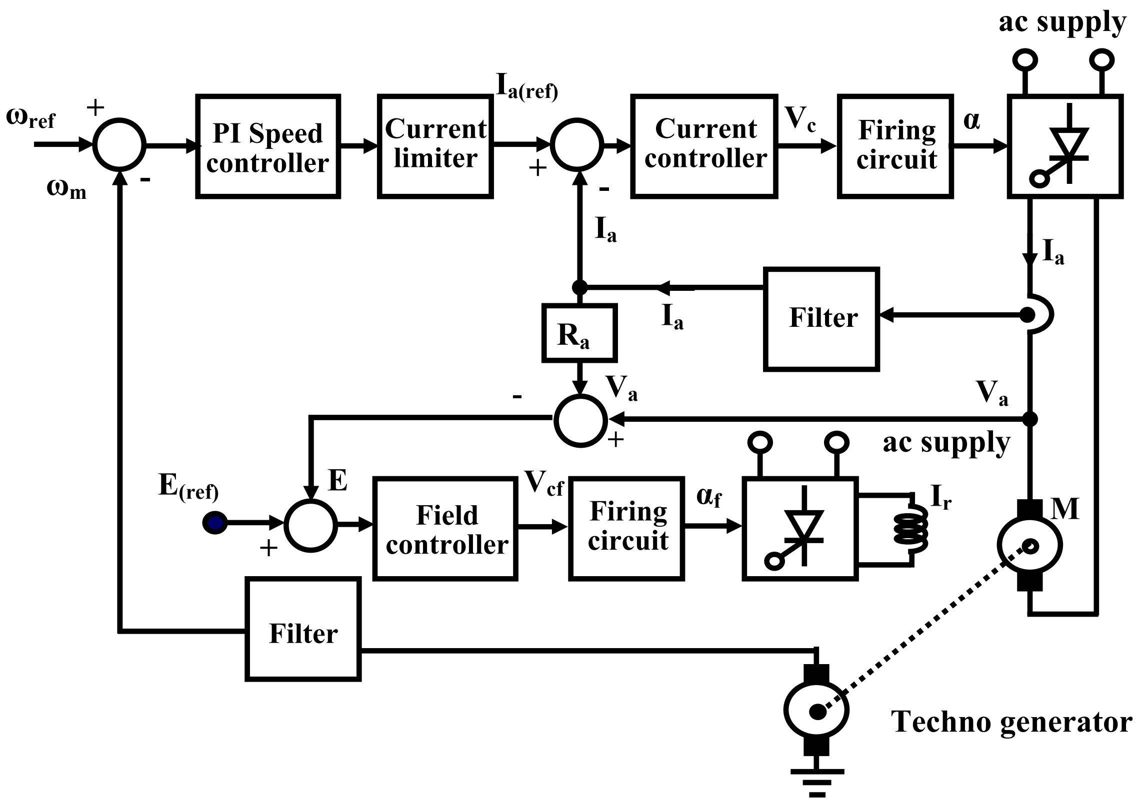


Fig. 33.12 Schematic of practical implemented of closed loop control for separately excited DC motor.

Points to Ponder: 3

A. *Draw the control loop structure for a position control application*
B. *Explain why the need for the filters and the current limiter in the block diagram of Fig. 33.12.*

Lesson summary

In this lesson, the following topics related to CNC machines have been discussed.

A. Reference pulse and reference word interpolators
B. Linear and Circular Interpolation
C. Digital Integration with a DDA
D. Open loop and closed loop control
E. Control of PTP and Contouring Systems
F. Characteristics of Feed and Spindle Drives

Points to Ponder: 1

A. *Why is it that dc motors are preferred for control applications, such as actuation, but ac motors are preferred for high power applications, such as compressors and fans ?*

Ans: Dc motors have simpler control and faster dynamic response, which is why it is preferred for servo applications. AC motors, on the other hand have better size to power ratio and lesser maintenance problems than DC motors, which is why they are preferred for large power applications.

B. *In a dc motor, is the field flux stationary or rotating? Is the armature flux stationary or rotating?*

Ans: In a DC motors both the field and armature fluxes are stationary in space, although the armature is rotating.

Points to Ponder: 2

A. *Can you identify some of the assumptions that have been made in the derivation of the above model?*

Ans: There are several assumptions. The first one is that of linearity which implies, among other things, that there is no flux saturation. Many factors are neglected, such armature inductance, armature reaction, brush drops. Friction is assumed viscous too. Many other assumptions can be found.

B. *What can you say about the input-output transfer function of the dc motor?*

Ans: The transfer function is first order. This is the result of neglecting the armature electrical time constant in comparison with the mechanical time constant. The transfer function would be second order too for a position control application, since the integrator between speed and position would now be included.

Points to Ponder: 3

A. *There are drives that are cheaper and permit restricted operations, such as operation only in 2 quadrants or even a single quadrant. What are the quadrants of operation if the dc motor is fed from a single phase fully controlled thyristor rectifier. Compare the resource requirements of this configuration with the one presented above.*

Ans: A single phase fully controlled rectifier can operate only in Quadrant I and IV. This is because, with such drives, while voltage can be reversed by controlling the firing angle, current cannot be reversed. Note that such drives can only be used for forward motoring, but not forward braking. The quadrant IV operation of regenerative braking can be used with loads that can drive the load in opposite directions, such as overhauling loads. For four-quadrant operation, two such drives must be connected in antiparallel.

Note that the number of devices required is also halved. For details see any standard text on Electric Drives.

B. *Can you describe what happens in dynamic braking?*

Ans: In dynamic braking the armature is connected across a braking resistor. The current continues in the same direction till the magnetic energy stored in the armature inductance is spent. Then, the back emf drives current in the reverse direction and mechanical power is spent as heat in the resistor, thus braking the motor.

Points to Ponder: 4

A. *Draw the control loop structure for a position control application.*

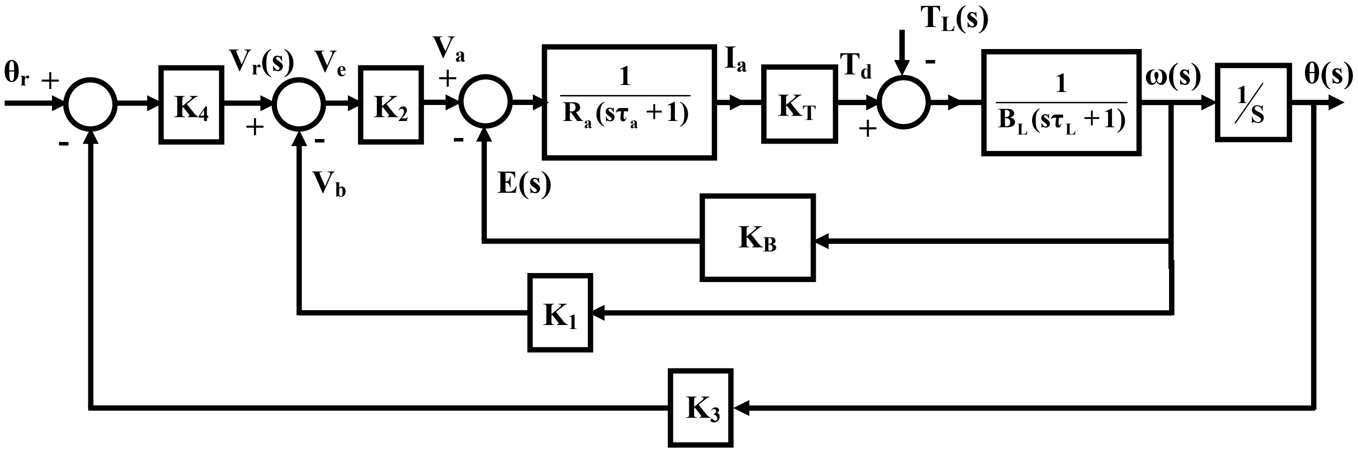


Fig. 33.13 Block diagram of closed-loop position control of separately excited DC motor.

B. *Explain why the need for the filters and the current limiter in the block diagram of Fig. 33.12.*

Ans: The current limiter is needed to avoid integrator windup in the current loop as well as to prevent peak current surges in the motor for large speed errors, while maintaining a high loop gain in steady state operations. The filters are needed to prevent sensor noise from causing noisy inputs into the motor.

Source:http://www.nptel.ac.in/courses/Webcourse-contents/IIT%20Kharagpur/Industrial%20Automation%20control/pdf/L-33(SM)%20(IA&C)%20((EE)NPTEL).pdf