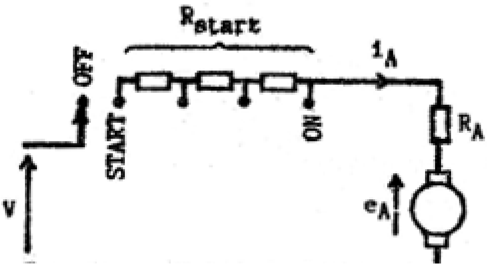
$$I_{start} = \frac{V}{R_A + R_{start}}$$



The value of Rstart is chosen to limit the starting current to a safe value, usually 1.5-2.5 times rated current. Although the starting current is still greater than the rated current, it is considered safe because it flows only for a short time. Moreover, a relatively high current is needed to obtain a high torque for rapid acceleration.

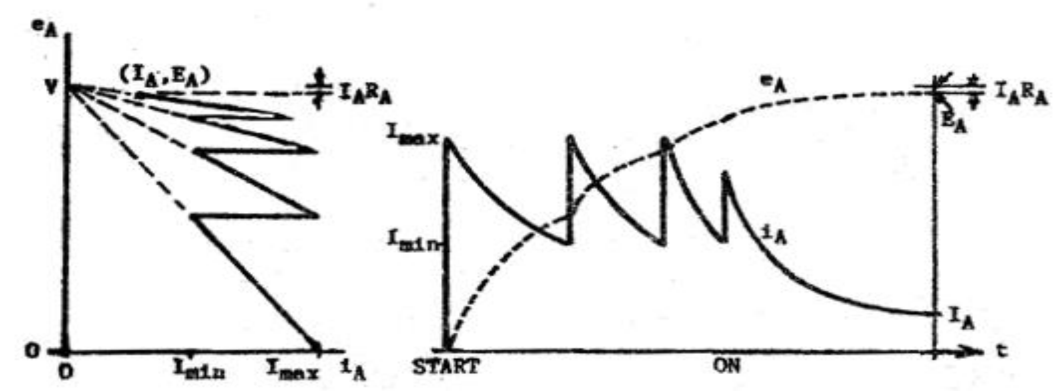


Fig. (9.22) Variation of armature current and induced emf during starting wit 3 switch starters.

As the motor builds up speed (and hence emf), the starting resistance is cut out section by section until it is totally out of the circuit. During this process, the starting current i and the induced emf eA follow stepped curves of the forms shown in fig. 9.22. In principle, a given section is cut out when the current has fallen to some minimum value, say rated current; upon cutting out the section, the current will jump up again to a value limited by the sections remaining in the circuit (maximum safe value).

During starting, full voltage must be applied to the shunt field winding to make the flux maximum; this maximizes starting torque, eqn 9.2, maximizes emf build-up, eqn 9.1, and prevents over speed (the high starting current may cause severe armature reaction, i.e. reduce the flux). For this reason, the starting resistor is connected in the armature circuit and not in the line, and the field control resistor is shorted out during starting.

9.10 Starters

A starter is a box that contains the starting resistor and other necessaries. Manual starters have a handle which the operator uses to cut out the starting resistor in steps. Fig. 9.23 shows a typical four-point starter. The studs (contacts)of the starting resistor are arranged in such a way as to ensure that the moving handle breaks contact with a stud only after it has contacted the next stud (why?). The starter of fig.9.23 has a number of protective functions that will be discussed later.

Automatic starters use relays instead of a handle; the contacts of the relays short out the sections of the starting resistor in sequence. The relays may be simple time delay relays, or they may be current sensitive relays (sections are cut out when the armature current falls below a preset value-Imin in fig. 9.22), or they may be voltage sensitive relays (sections are cut out when armature voltage rises above preset values).

The starter usually has additional relays, coils, and contactors to perform a number of functions. These include:

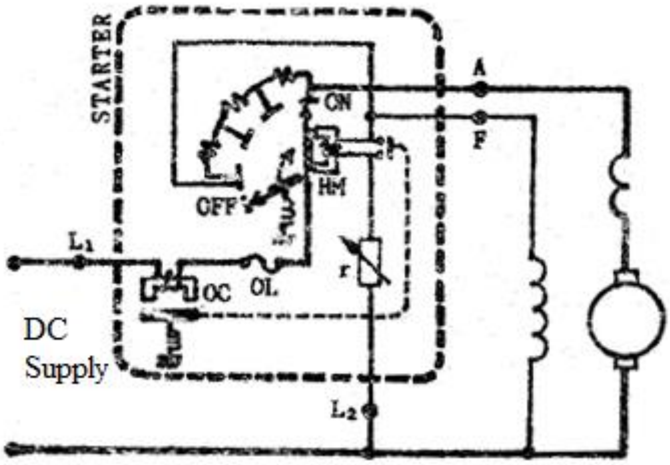


Fig. (9.23) Typical 4-point manual starter

Thermal overload protection (OL) :A temperature sensitive element set to disconnect the motor if the current exceeds rating for more than the permissible time; it works on an 'inverse-time' characteristic (i.e. it disconnects a slight overload after a long time, and a heavy overload after a short time).

Over-current protection (OC) :electromagnetic relay set to disconnect the motor instantaneously if the current begins to rise several times rated value (indicating short-circuits rather than mere overload).

No-volt trip : An electromagnet that returns the starting resistor to the OFF position when the supply voltage falls below a set value; this protects the motor from high starting current when the supply voltage is restored. In the starter of fig. 9.23, no-volt tripping is achieved by means of the holding magnet HM.

Loss-of field trip :electromagnetic relay set to disconnect the motor when the field current falls below a set value to prevent over speed.

Field discharge resistor :A resistor that is connected across the field winding at the instant the motor is switched off; it provides a path for the field current to decay safely (RL transient). Attempting to switch off the field current without a discharge resistor can produce a high voltage, Lfdif/dt, that may cause heavy sparking in the starter and electric shook to the operator.

9.11 Braking

When the electric supply to the motor is switched off, the rotation does not stop immediately, but continues until the kinetic energy of the rotating parts (rotor and load) is dissipated. But in many applications, such as electric trains, cranes, and lifts, the motor must be stopped quickly, so that some form of braking must be applied at switch-off.

9.11.1 External braking

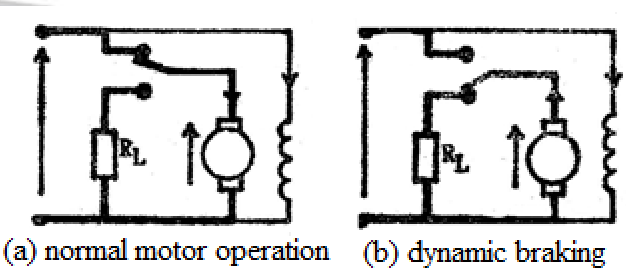
Quick braking can be achieved by an external friction brake mounted on the shaft and operated by a solenoid (electromagnet). At the instant the supply is switched off, the brake is applied to stop rotation. In effect, the kinetic energy of the rotating parts is dissipated quickly as heat in the brake pads.

The eddy-current brake is another type of external brake. It is made up of a conducting disc mounted on the shaft, and a set of stationary coils adjacent to the disc. At the instant the supply to the motor is switched off, the brake coils are energized to induce eddy currents in the rotating disc. The field of the coils and the currents of the disc produce a torque that opposes rotation (generator action) and hence slows the shaft rapidly. In effect, the kinetic energy of the rotating parts is dissipated as heat in the disc of the brake.

9.11.2 Electric Braking

Instead of using an external brake, it is sometimes possible to use the properties of the dc machine itself to achieve quick braking, or to assist in braking.

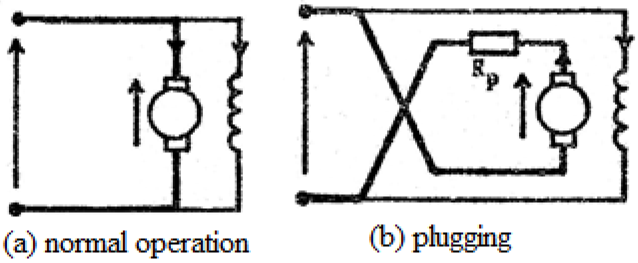
In dynamic braking (or rheostat braking), a resistor (possibly the starting resistor itself) is connected across the armature terminals at the instant it is disconnected from the supply, fig. 9.24. with the shunt field still excited, the machine acts as a generator loaded by the resistor; the armature current reverses, and the developed torque now opposes rotation. In effect, the kinetic energy is dissipated as heat (I2R losses) mainly in the resistor, but also in the armature wdg. During braking, it is preferable to energies the field from the line and not from the armature; otherwise, braking action stops when the speed falls below; the critical value (see section 8.5).



(a) normal motor operation (b) dynamic braking

Fig. (9.24) principle of dynamic braking

A dc motor is said to be regenerating when its emf exceeds the applied voltage so that the armature current reverses and the machine becomes a generator that returns electrical power to the supply; the source of the power is the kinetic energy of the rotating parts, and hence regeneration slows the motor down. Regenerative braking uses this principle to aid in stopping the motor or in slowing it down; regeneration is achieved by strengthening the field or by reducing the applied voltage. The main advantage of regenerative braking is the saving of energy, which is returned to the supply and not dumped as heat as in the other methods of braking. It is often used in electric trains to exploit downhill runs, and in cranes to exploit the descending part of the duty cycle. Regenerative braking can be used only if the electric supply is capable of accepting electrical energy from the motor (eg chargeable batteries or dc mains); standard controlled rectifiers cannot accept electrical power from the motor unless they ore modified for the purpose (eg by the inclusion of inverters). In regenerative braking, the braking action stops when the speed become low enough to reduce the emf below the terminal voltage.



(a) normal operation (b) plugging

Fig. (9.25) principle of plugging

A strong braking effect down to zero speed is obtained by plugging (or counter-current braking). The supply connections to the armature are reversed, fig. 9.25, so that the supply end armature emf act as series sources aiding each other to circulate a heavy counter-current:

$$I_A = \frac{E_A + V}{R}$$

The machine operates in the generating mode with a heavy current, and hence with a strong braking torque. A series limiting resistor, Rp, is inserted in the circuit to avoid damaging currents; if the starting resistor is used as Rp, the plugging current will be twice starting current, (i.e. up to five times rated current). During plugging the kinetic energy of the rotating parts plus heavy power from the supply (VIA)are dissipated in the armature winding and the limiting resistor Rp. The supply must be disconnected from the motor at the instant the speed reaches zero; otherwise the motor will run in the reverse direction. Plugging involves such heavy currents and high mechanical stresses that it is used only with small motors.

9.12 Modes of operation

The four-quadrant diagram of fig. 9.26 helps clarify the various modes of operation of a dc motor. The first quadrant corresponds to standard motor operation in one direction, while the third quadrant corresponds to motor operation in the reverse direction. The second and fourth quadrants correspond to generator operation.

Taking the first quadrant as reference, it is seen that motor operation in the reverse direction, third quadrant, requires reversal of either the applied voltage or the field current. If both are reversed at the same time, motor operation will continue in the same direction, first quadrant.

If initial operation is in the first quadrant, then the second quadrant corresponds to dynamic or regenerative braking. Plugging also shifts operation to the second quadrant, but attempts to continue to the third; the supply is disconnected when the operation point passes through zero speed. If initial operation is in the third quadrant, i.e. in the reverse direction, then dynamic braking, regenerative braking, and plugging occur in the fourth quadrant.

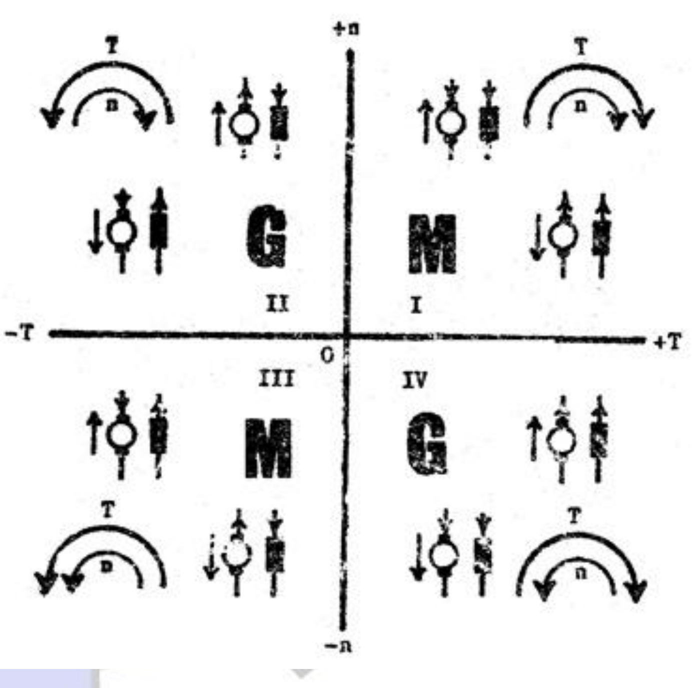


Fig. (9.26) Four-quadrant operation of DC motor.

For a lift or crane, we have:

Quadrant I :motor raises load;

Quadrant III **:**motor lowers load;

Quadrant II :motor brakes upward (inertia)motion of load;

Quadrant IV :load moves down by its own weight while motor applies a braking torque to keep speed constant.

9.13 Applications

DC motors are lass common than ac motors because ac motors are cheaper, more robust, and require less maintenance, and because standard mains are ac. However, there are two main types of application for which dc motors are more suitable than ac motors :battery-operated equipment, and applications requiring accurate or flexible control of speed or torque.

Battery-operated equipment includes small portable apparatus (cassette recorders, etc.), cordless tools, and toys, as well as electric drives in road vehicles. These are usually permanent-magnet or shunt (fixed-excitation) motors, but occasionally series motors. The high starting torque of the series motor makes it suitable for self-starter duty in cars. Electric vehicles employ permanent-magnet or series motors, with speed control by means of choppers (armature voltage control) or armature series resistance.

The accurate control of dc motors makes them suitable for servomotor duty in automatic control systems. The motors in such applications generally have small power rating (less than 1 KW), and are required to drive a load in accordance with a control signal applied to the armature (armature voltage control). They are usually constant field motors (PM or separately-excited) designed to have a low moment of inertia for quick response, and linear mechanical characteristics for accurate control, see fig. 9.20.

The flexibility of control of dc motors makes them suitable for certain heavy power applications such as lifts, cranes, and electric traction (electric trains), as well as certain drives in heavy industry. These app1icaticns can invo1ve frequent changes in speed, stops and starts, and possibly reversals. The hard characteristics of shunt motors with armature voltage control are ideal for adjustable1 speed drives, while the softer characteristics of compound and series motors are sometimes exploited in traction (locomotives)to do without different gear ratios.

9.14 Sheet ch.9

Unless otherwise stated, assume that (i) winding resistances are given at the working temperatures, (ii) the demagnetizing effect of armature reaction is negligible, and (iii)the brush contact drop is 2 volts. Some of the questions refer to the following machines and loads:

Machine M1 is a dc motor rated at 220 v, 1600 rpm, and 13.5 hp. The armature and shunt field resistances are 0.357 ohms and 55 ohms. The OCC is given in table 1 . it is known from tests that the torque due to rotational losses is approximately proportional to speed. The motor also has a series winding having 6 % of the shunt field turns and a resistance of 0.223 ohms; unless otherwise stated, assume the series winding to be disconnected.

Mac**hine M2** is a series motor whose armature and field resistances are 40 and 10 milliohms respectively. the occ is given in table 2. The brush contact drop may be assumed constant at 1v, and the rotational losses are approximately equal to 3n, where n is the speed in rps.

Machine tool load L1 has a torque-speed characteristic given by:

T = 8 + 1.7n .

fan load L2 has a torque-speed characteristic given by T = 9.6 + 0.05n2.

Table 1 OCC for M1at 1600 rpm.

Amps	volts
0.0	8
0.3	21
0.55	40
1.3	97
1.7	124
2.3	154
3.0	179
4.0	198
5.0	210
6.0	218
7.1	224
8.3	228

Table 2 OCC for M2 at 750 rpm.

Amps	Volts
0	0.0
3	2.0
5	3.5
7	4.7
10	6.45
15	8.45
20	10.1
25	11.35
30	12.35
35	12.9
40	13.4
50	13.92
60	14.2
75	14.3

1. A shunt motor runs on 250 V. the armature circuit resistance is 0.7 ohms, and the field circuit resistance is 25 ohms. For a certain load, the motor rotates at 1200 rpm and draws 100 A. (a) Find the developed torque when the motor current is 100 A. (b) find the motor current and shaft speed when the motor develops 300 Nm. (c)Estimate the no-load speed and the rate of change of speed with torque.
2. A PM motor runs from a 60 V supply, and has an armature resistance of 0.2 ohms. At no-load it draws 1.5 A and rotates at 900 rpm. The brush contact drop is 1v. (a) what is the full-load current if the full-