CHAPTER 9
MOTOR OPERATION

In motor operation, a dc machine is supplied electrically, and drives a mechanical load, fig. 9.1; compare with fig. 8.1 for the dc generator. This chapter explains the operating characteristics of a dc motors and the factors that affect them.

9.1 Governing Equations

In motor operation, we are interested in the output torque and shaft speed, and their influence on the current drawn by the motor. From previous chapters, the emf and torque equations for a dc machine are:

$E_A = K_e n\Phi$ (9.1)

And $T_d = K I_A \Phi$ (9.2)

Φ in these equations is the resultant useful flux per pole, i.e. it includes any demagnetization due to armature reaction. E_A is the actual induced emf, and T_d is the developed torque. From KVL, we have:

$E_A = V - (\sum IR + V_b)$ (9.3)

V is the voltage applied to the motor terminals, and ∑IR is the total series resistive drop (armature wdg, commutating wdg, compensating wdg, series field wdg, and any additional series resistance). To simplify our study, we shall approximate this equation to:

$E_A = V - I_A R$ (9.4)

I.e. the brash voltage drop is ignored, and R includes all resistances in the path of the armature currant. Dividing eqn 9.4 by $K_e\Phi$, and substituting eqn 9.1, we get:

$n = \frac{V - I_A R}{K_e \Phi}$ (9.5)

This equation tells us that speed is determined primarily by the applied voltage V and the flux Φ, with some reduction due to the series voltage drop $I_A R$ (which depends on current, and hence on load torque).

The above equations allow us to understand motor operation.

Load :torque and current

T_d in eqn 9.2 is the developed torque; it is slightly greater than the load torque T_L due to rotational losses (see chapter 7)

$T_d = T_L + T_{rot.\ loss}$ (9.6)

The greater the load on the motor, the greater the current it draws from the supply, eqn 9.2; that is the load torque determines the current of the motor.

Actually, eqn 9.6 holds only under steady state conditions, i.e. when the speed is constant. Under transient (or dynamic) conditions, the two sides of the equation are not equal, and the difference between them produces acceleration:

$$J\frac{dw_r}{dt} = T_d - (T_L + T_{rot\_loss}) \qquad (9.7)$$

Where J is the moment of inertia of the rotating parts (rotor, shaft, and load); dw_r/dt is the angular acceleration. Eqn 9.7 is a development from Newton's law F =ma (i.e. it relates to the mechanics of the system).

Suppose that the motor is running at some constant speed so that eqn 9.6 holds (i.e. $dw_r/dt = 0$ in eqn 9.7). Now suppose the load on the motor suddenly increases :the motor will slow down according to eqn 9.7. But this causes the induced emf to decrease, eqn 9.1. The resulting increase in the difference between V and E_A must be balanced by an increase in the armature current I_A, eqn 9.4. The increase in current increases the developed torque T_d, eqn 9.2, and the initial increase in load torque T_L is thus met. The motor now operates at steady state again, but at a reduced speed. The process is summarized as follows:

$T_L\uparrow \rightarrow n\downarrow \rightarrow E_A\downarrow \rightarrow I_A\uparrow \rightarrow T_d\uparrow$

9.7 9.1 9.4 9.2

The reverse process is summarized by:

$T_L\downarrow \rightarrow n\uparrow \rightarrow E_A\uparrow \rightarrow I_A\downarrow \rightarrow T_d\downarrow$

Note that if the series resistance in eqn 9.4 is small, then only a slight change in speed is sufficient to cause large changes in armature current (and hence in developed torque).

After a disturbance (sudden change in load), the time it takes the motor to settle at a new speed is called the response time. It is determined by the electrical time constant of the motor and the mechanical time constants of the motor and connected load. In certain applications, particularly automatic control system, the response must be quick, and the motor is designed to have low inductance and low inertia.

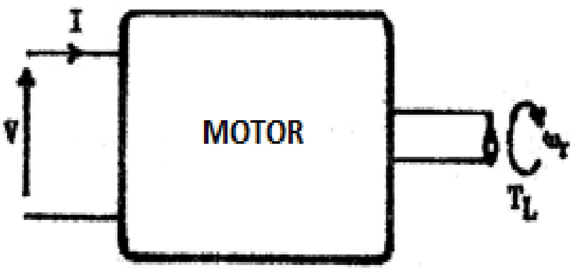


Fig. (9.1) Motor operation

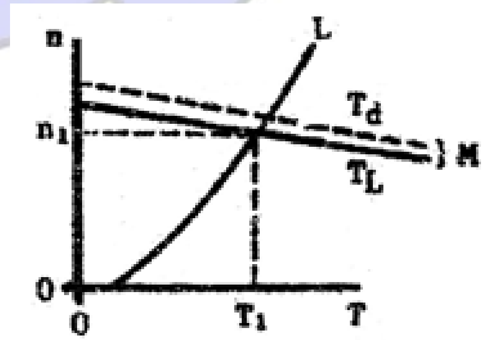
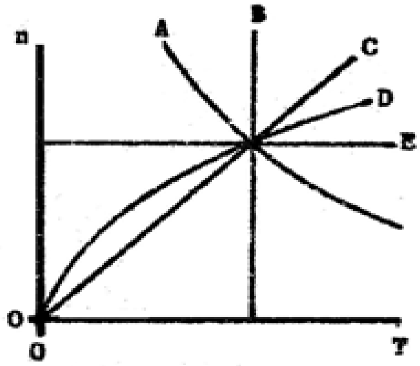


Fig. (9.2) intersection between mechanical characteristic and load



$A: T \propto \frac{1}{n}$ (constant power; traction)

$B: T = constant$ (traction; lifts; cranes)

$C: T = n$ (machine tools)

$D: T \propto n^2$ (fans; centerfugal pumps)

$E: n = constant$ (ac alternaters)

Fig. (9.3) Ideal load -speed / torque characteristic for typical mecancal load

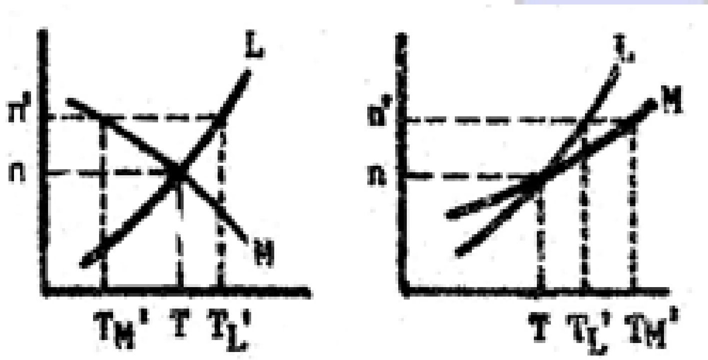


Fig. (9.4) Stability of operation point

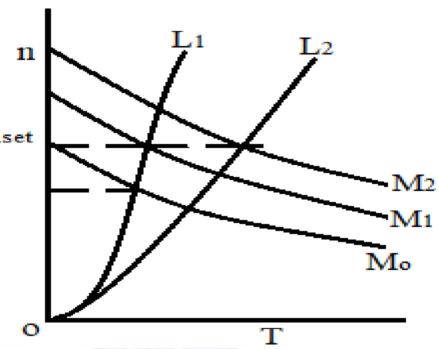


Fig. (9.5) Speed control of DC motor

9.2 Applied Voltage

The series resistance in the armature circuit is small, so that the induced emf E_A is approximately equal to the applied voltage V, eqn 9.4. Then, from eqn 9.1 we see that, for a given value of flux Φ, the speed is determined primarily by the applied voltage V.

9.3 Field Excitation

The flux Φ is determined primarily by the main field mmf (i.e. by field current), and may be controlled by field resistors as in fig. 8.2. The torque is directly proportional to flux, eqn 9.2, but the speed is inversely proportional to it, eqn 9.5. Thus, an increase in flux tends to decrease speed, and a decrease in flux tends to increase speed. Clearly, then, armature reaction tends to increase speed, while the series field in cumulative-compound motors tends to decrease speed.

9.4 Definitions

We shall need the terms and concepts defined below in our description of motor operation and the factors that affect it.

9.4.1 Mechanical characteristic

The mechanical characteristic of a dc motor is the curve relating the motor's two output variables, torque and speed; the curve shows how speed changes with load. Substituting for I_A from eqn 9.2 into eqn 9.5, we get:

$$n = \frac{V}{K_e \Phi} - \frac{R}{K_e K \Phi^2} T_d \qquad (9.8)$$

For constant V and Φ, eqn 9.8 represents a straight line with negative slope, fig. 9.2. The first term on the RHS gives the vertical intercept (no-load speed), and the coefficient of T_d in the second term gives the slope. The load torque T_L is a little less than the developed torque T_d, eqn 9.6, so that the relationship curves below the straight line. The shape of the curve may be further modified due to changes in the flux Φ (which affects both slope and intercept) as the motor load changes; the flux changes with load when there is a series field, when the demagnetizing effect of armature reaction is not negligible.

Note that eqn 9.5, and hence 9.8, are derived from KVL:

$$E_A = V - I_A R \qquad (9.9)$$

So that the straight line of fig. 9.2 is just a scaled representation of KVL.

When the motor is driving a mechanical load, the torque and speed are found from the motor mechanical characteristic and the load characteristic, fig. 9.2; that is, the operating point (T_1, n_1) is found graphically. Fig. 9.3 shows some typical characteristics of mechanical loads.

9.4.2 Stability

The operating point may or may not be stable. In fig. 9.4a it is stable :if the speed suddenly increases from n to n', the load torque T_L' will be greater than the motor torque T_M', causing deceleration back to the operating point (n, T); the operating point will also be restored to (n, T) for a sudden decrease in speed (try it). In fig. 9.4b, the operating point is unstable :if the speed suddenly increases from n to n', the motor torque T_M' will be greater than the load torque T_L', causing acceleration and further increase in speed away from the operating point (n, T); a sudden decrease in speed may result in stall (zero speed). Clearly, then, the stability of the operating point depends on the relative shapes of the motor and load torque-speed characteristics.

9.4.3 Speed control

Eqn 9.5 indicates that the speed may be controlled by means of the applied voltage, main flux, and the series resistance; these parameters may be adjusted manually or automatically. Although the armature current I_A appears in the equation, and hence affects speed, it is not a proper controlling parameter because it cannot be adjusted as desired, but is determined by the mechanical load, eqn 9.2.

New a given mechanical characteristic corresponds to a particular setting of the applied voltage, field control resistor, and series resistance. If any of the settings is changed, operation shifts to another curve. Therefore, the operating point may be moved from one curve to another by changing the setting of one or more of the control parameters, fig. 9.5. The speed may be kept approximately constant by automatic regulators that sense the shaft speed and adjust one of the control parameters to keep it at the set value.

9.4.4 Speed regulation

The speed regulation of a motor at a given load is defined by:

$$SR = \frac{n_0 - n_L}{n_L} \quad (9.10)$$

It is a figure of merit that indicates how constant the shaft speed is with load. For many applications, a good drive motor is one which maintains its speed constant over a wide range of loads. The speed regulation of motors equipped with automatic speed control is almost zero. Note the analogy between speed regulations in motor operation with voltage regulation in generator operation, section 8.2.

A low value of speed regulation is not always desirable. There are applications that require the motor to change its speed with load, for example to keep the torque or output power constant. A main feature of the dc motor is that its operation can be tailored to suit any type of load requirements.

9.5 Constant-Flux Motors (Permanent-Magnet; Separately-Excited; Shunt)

The difference between shunt and separately excited motors is that the field of a shunt motor is fed from the same source as the armature, while the field of a separately excited motor is fed from a different source, possibly at a different voltage. In both cases, constant field voltage and resistance result in constant field current (If does not change with load), and hence constant main field flux. Permanent magnet motors also operate with a constant main field.

If the demagnetizing effect of armature reaction is neglected, the developed torque Td will be directly proportional to the armature current IA, eqn 9.2, so that the two variables are related by the straight line shown dotted in figure 9.6. Armature reaction may reduce the flux Φ, and hence reduce Td, so that the actual relationship between Td and TL is curved slightly below the straight line. The load torque TL is less than the developed torque Td due to rotational losses, eqn 9.6 so that the TL curve is slightly below the Td curve, fig. 9.6. The relationship between torque and current is sometimes called the torque characteristic of the motor.

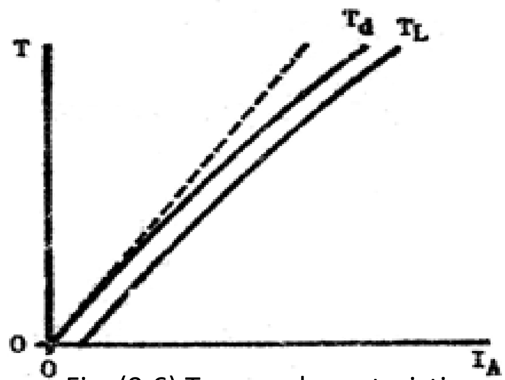


Fig. (9.6) Torque characteristic

For constant-flux motors, the mechanical characteristic is a straight line with a slight negative slope, eqn 9.3 and fig.9.7. Armature reaction may reduce useful flux and hence increase the speed, so that the mechanical characteristic curves slightly above the straight line. This upward curvature may lead to instability, section 9.2; it is avoided by designing the motor to have no demagnetizing armature reaction (by the use of interpoles), and by adding a weak series field to compensate for the reduction in flux (stabilized shunt motor).

The reduction in speed with load is very small for constant-flux motors. The mechanical characteristic is said to be hard, and the motors operate in an essentially constant speed mode.

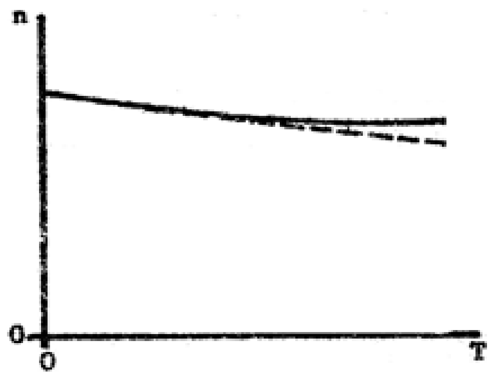


Fig. (9.7) mechanical characteristic

9.6 Series Motor

The main field flux of the series motor changes with load current according to the OCC; therefore, the series motor is characterized-by variable flux, as opposed to the constant flux motors of section 9.5.

At light loads, operation is on the linear part of the OCC, so that:

$\Phi \propto I_A$

And eqn 9.2 yields,

$T_d \propto I_A^2$

Thus, the torque characteristic follows a parabola at light loads, fig. 9.8. At heavy loads, the machine will be saturated so that the flux is almost constant, and operation approaches that of constant-flux motors

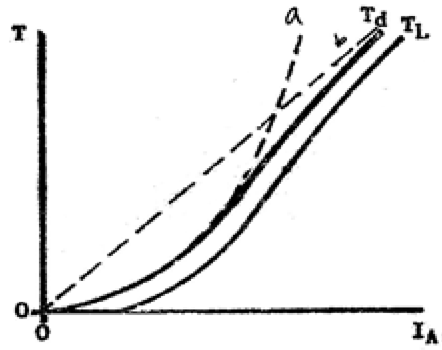


Fig. (9.8) Torque characteristic

Φ =constant → $T_d \propto I_A$

The torque characteristic approaches a straight line at heavy loads, fig.9.8.

Applying the same reasoning to the mechanical characteristic, we see that

At light loads: $n \approx \frac{k_1}{\sqrt{T_d}} - k_2$

And

At heavy Loads :$n \approx K_3 - K_4 T_d$ (similar to shunt)

The mechanical characteristic will then have the general shape shown in fig. 9.9. The change of speed with load is quite large; the mechanical characteristic is said to be soft, and the series motor operates in a variable speed mode. The motor has a high starting torque, but the torque quickly decreases as speed goes up. At no-load the speed becomes so high it can damage the motor; therefore, series motors are never run unloaded, and are always rigidly coupled to their loads (i.e. belts are never used).

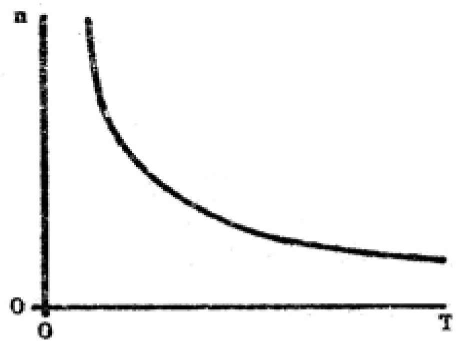


Fig. (9.9) Mechanical

9.7 Compound Motors

A compound motor has both shunt and series fields. For cumulative compounding, the motor characteristics will move from shunt characteristics in the direction of series characteristics as load increases (i.e. as the series field becomes stronger); see

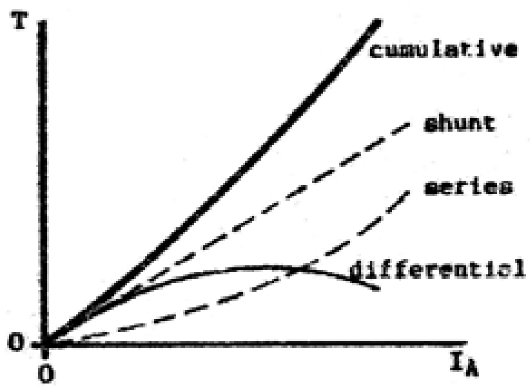


Fig. (9.10) Torque characteristic

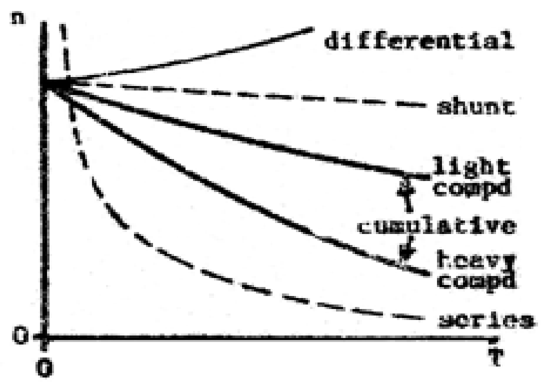


Fig. (9.11) Mechanical characteristic