figures 9.10 and 9.11. The actual shape of the mechanical characteristic is determined by the degree of compounding, i.e. by the ratio Ns/Nf, fig. 9.11. Differential compound motors have rising mechanical characteristics because of the reduction in main field flux with load, fig. 9.11; therefore, they are unstable (section 9.4), and are not used in practice.

9.8 Speed Control

According to eqn 9.5, the parameters that can be adjusted to control speed are :the voltage applied to the armature V, the series resistance R, and the field excitation I_f (which determines main field flux).

9.8.1 Armature Voltage Control

For constant flux motors, section 9.5, the torque-speed equation 9.8 describes a straight line, fig. 9.7. The first term on the RHS gives the intercept, and the coefficient of Td in the second term gives the slope, which is negative. In permanent-magnet and separately-excited motors, the voltage applied to the motor can be varied with the field remaining constant. Different voltages then give different intercepts, and we get a family of parallel (i.e. same slope) mechanical characteristics as in fig. 9.12. In the figure, Vr denotes rated voltage; as the applied voltage is decreased, the characteristic is shifted down. Similar downward shifts occur for the series motor, fig. 9.13; at heavy loads, the series motor approaches constant-flux operation, section 9.4, and the curves approach straight lines that are parallel as in fig. 9.12.

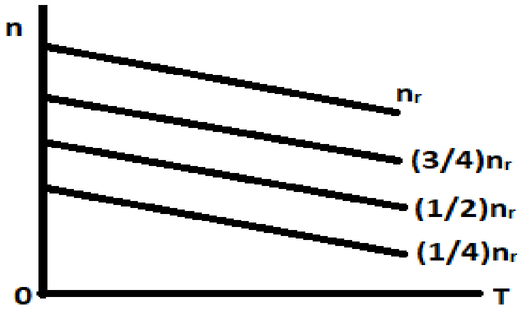


Fig. (9.12) voltage control for constant flux DC machine

The simplest method of obtaining variable dc voltage is to use a voltage divider, out this method is impractical and uneconomical; it is used only for testing.

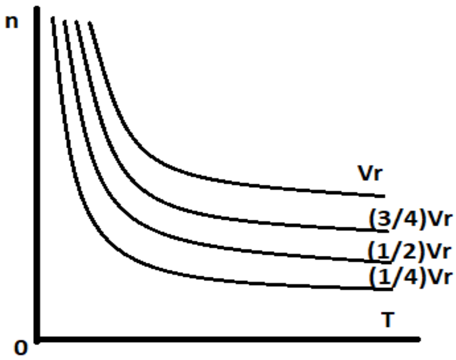


Fig. (9.13) voltage control for series DC machine

In modern applications, variable dc voltage for the armature is often obtained from a solid-state controlled rectifier, with the field fed from an uncontrolled rectifier, fig. 9.14. The firing angle of the controlled rectifier may be changed manually, but in practice it is adjusted automatically using a speed signal or armature current signal (i.e. load), or both for optimum control.

In road vehicles, the supply is itself dc, and

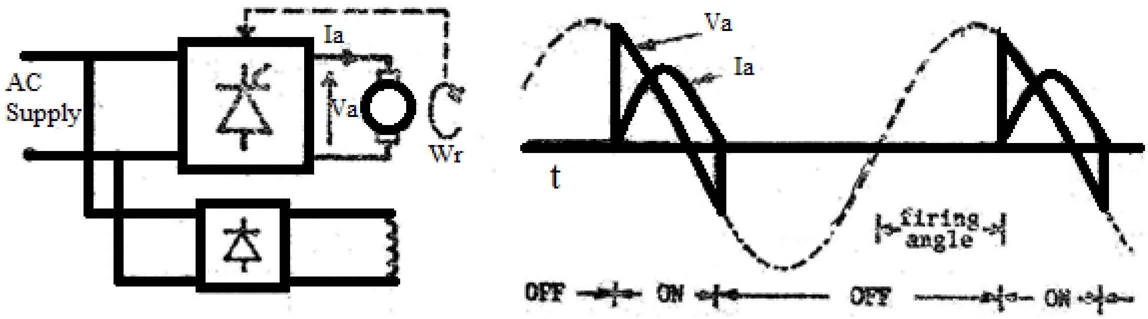
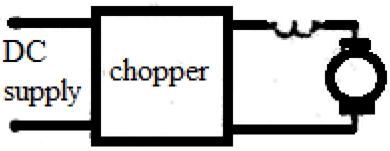


Fig. (9.14) Armature voltage control using solid- state controlled rectifier.



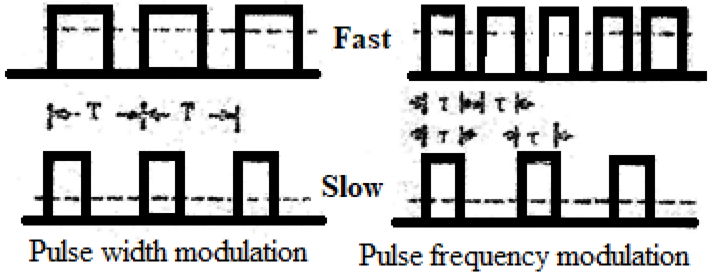


Fig. (9.15) Armature voltage control for series motor using chopper DC supply.

hence needs no rectification. Voltage control is often obtained by an electronic chopper circuit, fig. 9.15. Choppers may use pulse-width modulation PWM at constant frequency, or pulse-frequency modulation PFM with constant pulse width.

Another effective method for obtaining smooth voltage control is the ward-Leonard system, fig. 9.16. The dc motor is fed from a dc generator driven by some prime-mover (eg ac motor or Diesel engine). By varying the field excitation of the generator, the armature voltage of the motor is varied (and can be even reversed). The motor field is fed from an exciter (smell dc generator) or rectifier at constant voltage. The Ward-Leonard system is generally more expensive then a solid-state drive, but has compensating advantages for certain applications.

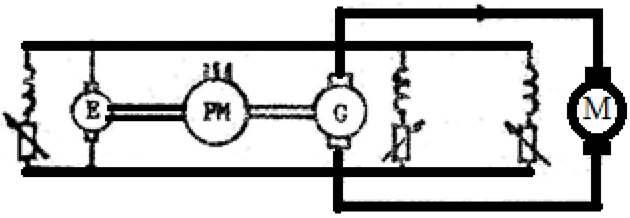
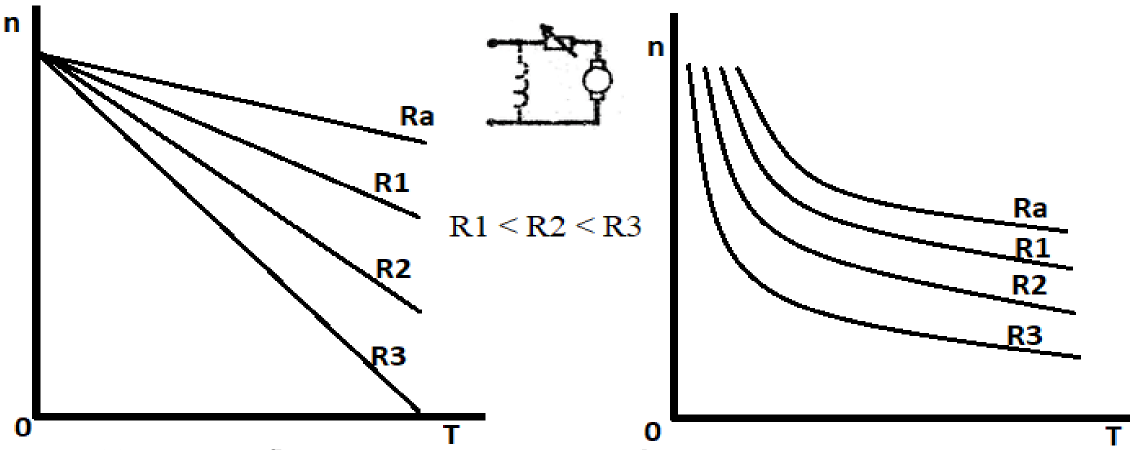


Fig. (9.16) Ward-Leonard system for armature voltage control

9.8.2 Armature Resistance Control

For a given load torque, and hence given current, placing an external resistance in series with the armature, fig. 9.17, reduces the emf and hence speed. The increasing value of resistance increases the slope of the mechanical characteristic, eqn 9.8. Thus, the hard characteristic of constant-flux motor is seen to become softer with increasing resistance in fig. 9.17a, but the intercept remains unchanged. Armature resistance control may also be used with series motors giving the family of curves shown in fig. 9.17b; at heavy loads the machine is saturated (why?) and operation approaches that of constant-flux motors with slope increasing as resistance is increased.



(a) Constant flux motor (b) series motor

Fig. (9.17) Armature resistance control

Armature resistance

control is inexpensive and simple to use with small motors, but it is impractical and wastes energy with large motors.

9.8.3 Field Control

This method of speed control may be used with shunt and separately excited motors. With no external resistance in the field circuit, and with rated voltage applied to the armature, the motor will operate at constant flux and follow a certain mechanical-characteristic; this is called the base case, fig. 9.18. If now the field circuit resistance is increased, the field current, and hence the main field, will be reduced, and the speed will increase according to eqn 9.5 or 9.8. We thus obtain a family of curves above the base case, fig. 9.18. The higher the field resistance, the higher the intercept and the greater the slope (i.e. the characteristic becomes softer).

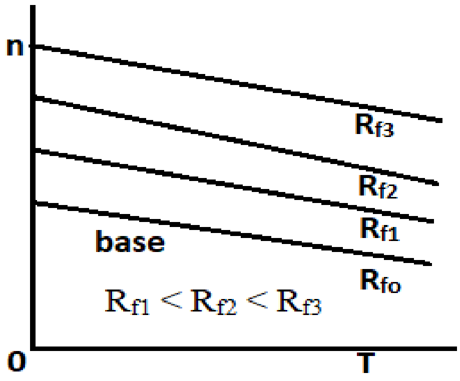


Fig. (9.18) Field control

The flux cannot be reduced indefinitely because the speed becomes too high and may damage the motor. Moreover, if the main field becomes too weak, the demagnetising effect of armature reaction becomes prominent (relatively large) which may lead to instability, section 9.4.

9.8.4 Comparison

Armature voltage control provides the best method of speed control of dc motors; indeed, it is the main reason for the continuing existence of large dc machines. The speed may be controlled from zero to maximum safe speed in either forward or reverse direction. The control can be manual, or automatic with speed or current sensors. The constant-speed feature of constant-flux motors is retained, giving adjustable speed drives.

Armature resistance control is cheaper than armature voltage control, but it is wasteful and less versatile. As the armature resistance increases, the mechanical characteristic becomes softer, and the motor operates at variable-speed. This type of control is sometimes used with relatively small series or permanent magnet motors.

Shunt field control is also relatively cheap (and wasteful); but it does not compete with armature voltage control :it increases speed from base value, and cannot reduce speed to zero. The mechanical characteristic becomes softer as the field resistance is increased, and there is an upper limit on the speed that can be reached, usually around 2:1 (i.e. twice base speed).

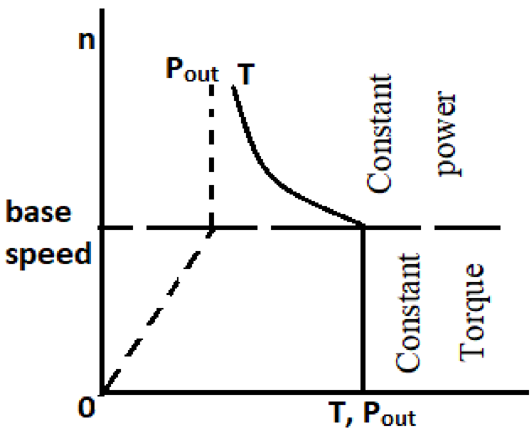


Fig. (9.19) Armature voltage control up to base speed, with field weakeaing to exteed speed

In some applications, particularly traction, both armature voltage and field control are used, fig. 9.19 :armature voltage control is used up to base speed to maintain the torque constant; above base speed, field control is used to maintain output power constant (2πnT).

Small dc motors with fixed excitation are often used in automatic control systems. They are designed to have linear mechanical characteristics with accurate voltage control down to stall (standstill)as shown in fig. 9.20.

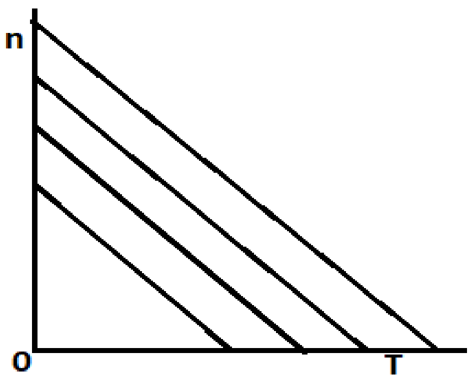


Fig. (9.20) Control motor characteristic.

9.9 Starting

At the moment the motor is switched on, it is at standstill, so that there is no induced emf. The entire line voltage is applied across the armature resistance since eqn 9.4 reduces to Ohm's law:

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

The starting current is therefore very high, especially for large motors which have very small armature circuit resistance. The starting current may be more than 20 times rated value, and would damage the motor unless some means is found to limit it.

Note that the problem exists only at starting because as soon as the motor begins to rotate, the emf begins to build up and thus reduce the current in accordance with eqn 9.4. Note also that the rate at which the emf builds up depends on the rate at which the motor accelerates from standstill which, in turn, depends on the starting torque; that is, a high starting torque is desirable for rapid initial acceleration (and hence rapid build-up of emf and hence rapid reduction of the high starting current).

9.9.1 Direct On-Line Starting (DOL)

DOL starting means simply connecting the motor to the supply through a switch. This method can be used only with small motors where (a)the armature resistance is high enough to limit the starting current, and (b)the rotor inertia is small enough to allow rapid acceleration (and hence rapid buildup of mmf leading to rapid reduction of current).

9.9.2 Variable Voltage Starting

Motors supplied from Ward-Leonard sets or controlled rectifiers can be started by raising the supply gradually from zero. The low initial voltage results in a reduced starting current.

9.9.3 Resistance Starting

This is the most common method of starting do motors. A specially designed variable resistor is connected in series with the armature, fig. 9.21. When the moving contact is moved from the OFF position to the START position, all sections of the starting resistor or in the circuit so that the starting current is limited to: