

Speed Control of a DC Motor

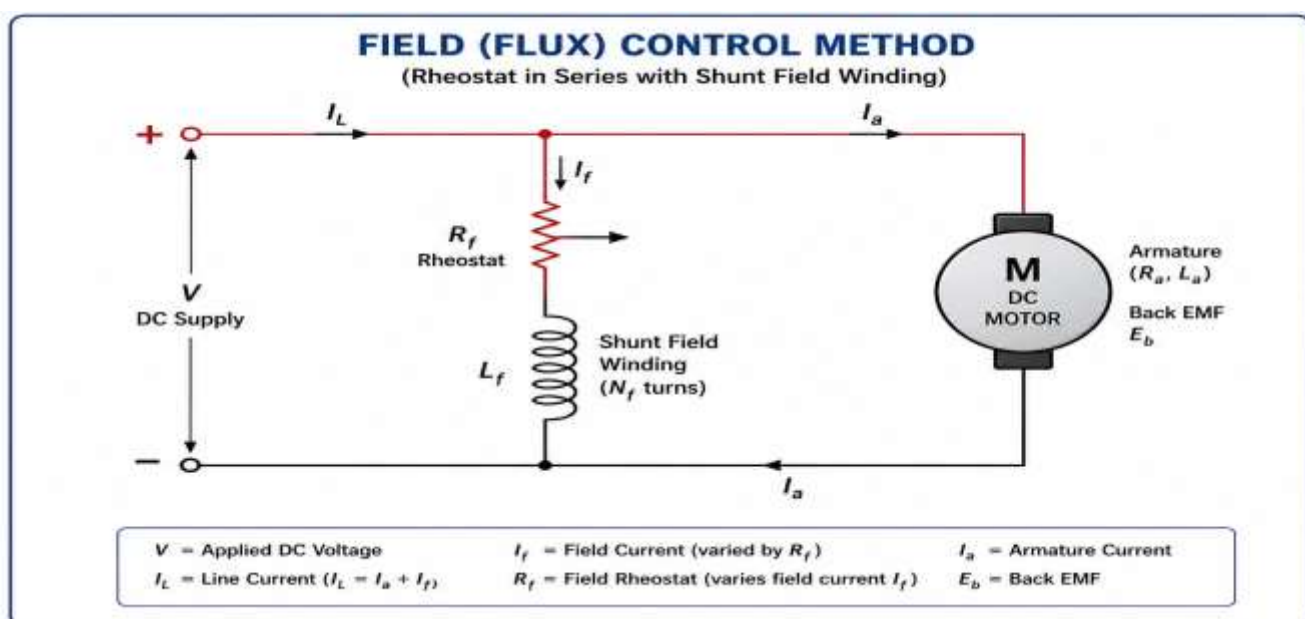
In many industrial applications, it is necessary to run a DC motor at a speed other than its normal rated speed, or to vary its speed continuously to suit changing load requirements. The starting point for understanding speed control is the relationship between the back EMF, the flux and the speed of a DC motor, obtained by combining the EMF equation with the voltage equation of a motor:

$$N \propto Eb / \phi, \text{ where } Eb = V - IaRa$$

This relationship shows that the speed N can be controlled by varying any one of three quantities: the flux ϕ , the voltage drop in the armature circuit (by inserting resistance), or the applied voltage V itself. These give rise to three principal methods of speed control, discussed in turn below.

Field Control Method (Flux Control)

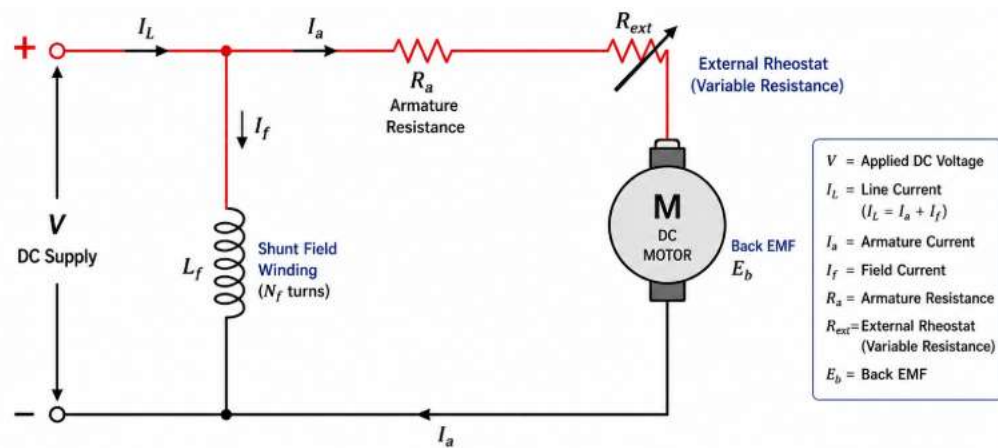
In this method, a rheostat is connected in series with the field winding, so that the field current — and consequently the flux ϕ — can be varied. Since speed is inversely proportional to flux, reducing the field current (and hence ϕ) causes the speed to rise above the normal rated value. This method therefore provides speed control above the rated speed only. It is simple, economical, and involves comparatively little power loss, since the field current is small compared with the armature current. However, the method has its limits: if the flux is reduced too far, the speed may rise to an unsafe value, and since torque is proportional to the product of flux and armature current, the available torque falls as the flux is reduced. This method finds application in machine tools and other drives where an increase in speed above normal, with reduced torque, is acceptable.



Field (flux) control method

Armature Control Method (Rheostat Control)

In the armature control method, a variable resistance is connected in series with the armature circuit. The insertion of this resistance increases the voltage drop $I_a R_a$ across the armature circuit, thereby reducing the effective back EMF and, consequently, the speed, since the speed is proportional to $(V - I_a R_a)$. This method gives speed control below the normal rated speed only. Although it is simple and inexpensive to implement, it suffers from the serious disadvantage that a substantial amount of power is dissipated as heat in the series resistance, making the method inefficient, particularly for large motors; furthermore, the speed obtained is not independent of load, since the voltage drop across the rheostat itself depends on the armature current drawn by the load. Because of this, the method is generally restricted to small motors and to applications such as cranes, hoists and traction motors, where the speed reduction is required only for short intervals.



Armature control method

Voltage Control Method

The third approach is to vary the voltage applied to the armature directly. Two variants of this method are commonly used in practice.

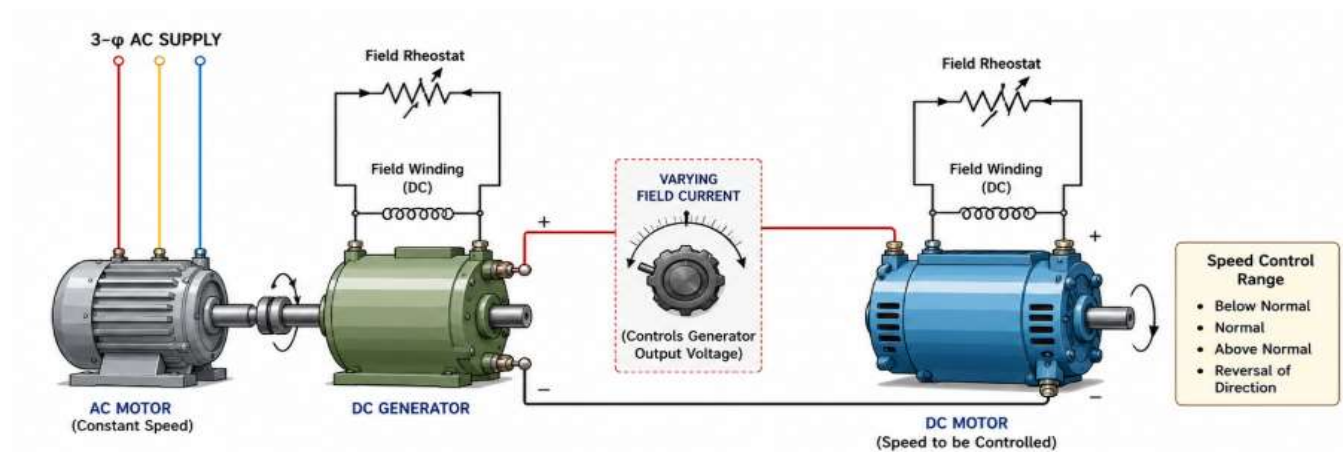
(a) Multiple Voltage Control

Here, the armature of the motor is connected, through appropriate switchgear, to one of several different fixed supply voltages. Because only a limited number of fixed voltages are available, the speed can be varied only in steps, rather than continuously.

(b) The Ward-Leonard System

The Ward-Leonard system is used where smooth speed control over a wide range is required, particularly in large motors. In this arrangement, a separately excited DC generator, driven at constant speed by an AC motor, is used to supply variable voltage directly to the armature of the DC motor whose speed is to be controlled. By varying the field current of the generator — and

hence its output voltage — the voltage applied to the armature of the driven motor can be smoothly varied from zero up to its full rated value, and even reversed in polarity. This allows speed control both above and below the normal rated speed, and permits smooth reversal of the direction of rotation as well. Although the Ward-Leonard system is costly, requiring an additional motor-generator set and occupying considerable space, it offers smooth control, a wide speed range, and comparatively high efficiency; for this reason, it is widely used in large lifts, mine winders, electric excavators and steel rolling mills.



The Ward-Leonard speed control system

Comparison of Speed Control Methods

Method	Quantity varied	Range obtained	Efficiency
Field control	Flux, ϕ	Above normal speed	High
Armature (rheostatic) control	Armature-circuit resistance	Below normal speed	Low
Ward-Leonard (voltage) control	Applied voltage, V	Above and below normal speed	Moderate to high

EMF and Torque Equations

Having studied the construction and principle of operation of DC machines, we now derive the two fundamental equations that govern their performance: the EMF equation and the torque equation. Together, these equations connect the electrical quantities (flux, armature current) with the mechanical quantities (speed, torque) of the machine, and form the basis for solving numerical problems on DC machines.

EMF Equation

Consider a DC machine with the following notation: P is the number of poles, ϕ is the flux per pole in weber, Z is the total number of armature conductors, N is the speed of the armature in revolutions per minute, and A is the number of parallel paths in the armature winding (A = P for a lap winding, A = 2 for a wave winding).

In one complete revolution of the armature, every conductor cuts the flux of all P poles, so that the total flux cut per conductor per revolution is $P\phi$ webers. Since the armature makes N revolutions per minute, the time taken for one revolution is $t = 60/N$ seconds. The average EMF induced in one conductor is therefore:

$$e = P\phi \div (60/N) = P\phi N / 60 \text{ volts}$$

Since the Z armature conductors are connected in A parallel paths, each path contains Z/A conductors in series, and the EMFs of these conductors add up. The total EMF generated across the brushes — denoted E_g for a generator and E_b for a motor, since the same physical quantity plays both roles — is therefore:

$$E_g \text{ (or) } E_b = P\phi ZN / 60A \text{ volts}$$

Note

For a lap-wound armature, A = P, and the EMF equation reduces to $E_g = \phi ZN/60$, independent of the number of poles. For a wave-wound armature, A = 2, giving $E_g = P\phi ZN/120$.

Voltage Equations

For a DC generator, the terminal voltage V available to the external load is less than the generated EMF by the voltage drop in the armature resistance:

$$V = E_g - I_a R_a$$

For a DC motor, the applied voltage V has to supply both the back EMF and the drop across the armature resistance:

$$V = E_b + I_a R_a \quad \text{i.e.} \quad E_b = V - I_a R_a$$

Torque Equation

The torque developed by the armature of a DC machine can be obtained from the principle of conservation of energy: the electrical power associated with the back EMF must equal the mechanical power developed in the armature. If T is the torque developed, in newton-metres, and the armature rotates at N revolutions per minute (so that its angular velocity is $2\pi N/60$ radians per second), then:

$$E_b I_a = 2\pi NT / 60 \text{ watts}$$

Substituting the expression for E_b from the EMF equation of Section 3.5.1:

$$(P\phi ZN / 60A) I_a = 2\pi NT / 60$$

The speed N cancels from both sides of this equation, leaving:

$$T = P\phi ZI_a / 2\pi A \text{ newton-metres}$$

This is often written in decimal form for convenience in calculation as:

$$T = 0.159 (P\phi ZI_a / A) \text{ N-m}$$

Note

Since $T \propto \phi I_a$, the torque of a DC motor depends jointly on the flux and the armature current. In a shunt motor, where the flux remains nearly constant, torque is directly proportional to the armature current ($T \propto I_a$). In a series motor, however, the flux itself is (before saturation) proportional to the armature current, so that $T \propto I_a^2$ — this quadratic relationship explains why series motors develop a very high starting torque and are therefore preferred for traction and crane applications.

Applications of DC Generators and DC Motors

The choice of a particular type of DC generator or DC motor for a given application depends primarily on its terminal characteristics — that is, how its output voltage (for a generator) or its speed and torque (for a motor) vary with load current. DC machines are classified according to the way the field winding is connected with respect to the armature: separately excited, shunt, series, and compound (cumulative and differential). Each type possesses distinct characteristics that make it suitable for specific applications, as discussed below.

A. Applications of DC Generators

DC generators are classified based on the method of field excitation into: Separately Excited Generator, Shunt Generator, Series Generator, and Compound Generator (Cumulative and Differential). Their characteristics and applications are as follows.

1. Separately Excited Generator

In this type, the field winding is excited from an independent external DC source, so the field current is entirely independent of the armature current and terminal voltage. This gives excellent voltage regulation and allows the output voltage to be controlled smoothly over a wide range, including zero and reversal of polarity.

- Applications: Used in the Ward-Leonard speed control system for large DC motors; used for electroplating and electro-refining processes requiring very smooth, ripple-free, and precisely

controllable DC voltage; used in testing laboratories where accurately variable DC supply is required.

2. Shunt Generator

Here, the field winding is connected in parallel (shunt) with the armature, so the field current is a small fraction of the armature current and depends on the terminal voltage. The terminal voltage falls only moderately with increasing load, due to armature resistance drop, armature reaction, and the consequent fall in field current. It gives reasonably flat voltage regulation for a limited range of load and possesses inherent short-circuit protection, since the terminal voltage (and hence field current) collapses under a heavy overload.

- Applications: Battery charging; supplying general lighting and power loads in isolated installations; as an exciter for supplying the field current of large AC alternators; general industrial power supply where the load is fairly steady.

3. Series Generator

In a series generator, the field winding is connected in series with the armature and carries the full load current. As the load current increases, the flux (and hence the induced EMF) increases considerably, so that the terminal voltage rises sharply with load, up to the point of magnetic saturation. Because of this rising characteristic, series generators are rarely used for ordinary power supply purposes, but their special voltage-boosting property makes them useful in specific applications.

- Applications: Used as boosters to compensate for the voltage drop in feeders and transmission lines (connected in series with the line so as to add a boosting voltage proportional to the load current); used in series arc lighting circuits, where a constant current rather than constant voltage is required.

4. Compound Generator

A compound generator has both a shunt field winding and a series field winding on the same pole. Depending on whether the series field assists or opposes the shunt field, compound generators are further classified as cumulatively compounded (series flux adds to shunt flux) or differentially compounded (series flux opposes shunt flux).

- Cumulative Compound (Flat-compounded): Designed so that the terminal voltage at full load is equal to the voltage at no load, the rise in EMF due to the series field exactly compensating for the armature resistance drop and armature reaction. Used for general power supply purposes where constant terminal voltage is required irrespective of the load, such as in office and factory lighting and power distribution.
- Cumulative Compound (Over-compounded): Designed so that the full-load terminal voltage is higher than the no-load voltage, to compensate for the voltage drop in long feeders or transmission lines between the generator and the load. Used for supplying power over long

feeders, such as in railway service and distribution systems where the load centre is far from the generating station.

- **Differential Compound:** The terminal voltage falls rapidly as the load current increases, giving a drooping characteristic. Used in applications demanding a constant-current output rather than constant voltage, such as in DC arc welding generators, where the welding current must remain nearly constant despite variation in arc length (arc resistance).

B. Applications of DC Motors

DC motors are also classified according to the connection of the field winding into: Shunt Motor, Series Motor, Cumulative Compound Motor, and Differential Compound Motor. Their choice for a given application depends on the nature of the speed-torque and speed-armature-current characteristics required.

1. DC Shunt Motor

In a shunt motor, the field winding is connected across the armature and is supplied at (nearly) constant voltage; hence the flux remains practically constant regardless of the load. Since speed $N \propto E_b/\phi$ and back EMF changes only slightly with load, the shunt motor maintains an almost constant speed from no-load to full-load — it is essentially a constant-speed motor. Its starting torque is moderate ($T \propto I_a$, since ϕ is constant).

- **Applications:** Lathes and other machine tools requiring constant speed; centrifugal pumps; blowers and fans; conveyor belts; drilling machines; and other industrial drives where speed must remain sensibly constant irrespective of load variation.

2. DC Series Motor

In a series motor, the field winding is connected in series with the armature and therefore carries the full armature (load) current. Before magnetic saturation, the flux ϕ is directly proportional to the armature current I_a , so torque $T \propto I_a^2$ — the series motor develops a very high starting torque, far greater than a shunt motor of the same rating for the same starting current. Its speed varies inversely with the load: speed is very high at light load (and dangerously high, even to the point of 'running away', at no load) and falls considerably as the load — and hence the current — increases. Because of this characteristic, a series motor must never be started or run without a mechanical load coupled to its shaft.

- **Applications:** Electric traction (locomotives, trams, and electric trains), where high starting torque is essential to accelerate a heavy load from rest; cranes and hoists, where a heavy load must be lifted from standstill; electric trolleys; and starter motors used for cranking automobile and diesel engines.

3. Cumulative Compound Motor

This motor has both series and shunt field windings so connected that their fluxes add together (aid each other). It combines the desirable features of both shunt and series motors: it develops a high starting torque (though less than a pure series motor) contributed by the series field, while the shunt

field prevents the dangerous no-load speed rise associated with a series motor, since the shunt field alone maintains a finite flux even when the load — and hence the series-field current — falls to a low value.

- Applications: Used where a high starting torque is required together with fairly constant, safe running speed, such as in lifts and elevators, rolling mills, punching and shearing machines, heavy planers, and reciprocating machinery such as compressors and pumps subject to sudden load fluctuations.

4. Differential Compound Motor

Here, the series field winding is connected so that its flux opposes the shunt field flux. As the load increases, the opposing series flux reduces the net flux, which tends to increase the speed with increasing load — a rising speed characteristic. This behaviour is generally undesirable and can lead to instability under heavy load; consequently, differential compound motors are rarely used in practice.

- Applications: Limited to a few special applications requiring a rising speed characteristic with load, such as in certain experimental and laboratory setups; otherwise, this type finds negligible use in industry because of its inherently unstable operating characteristic under overload.