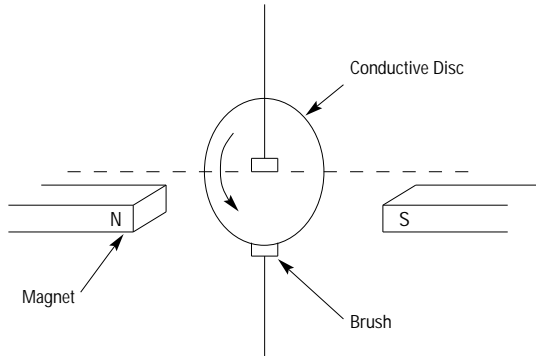


## DC Brush Motors

The history of the DC motor can be traced back to the 1830s, when Michael Faraday did extensive work with disc type machines (Fig. 1.21).

*Fig. 1.21 Simple disc motor*



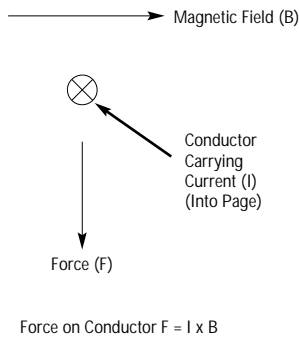
This design was quickly improved, and by the end of the 19th century the design principles of DC motors had become well established.

About that time; however, AC power supply systems came into general use and the popularity of the DC motor declined in favor of the less expensive AC induction motor. More recently, the particular characteristics of DC motors, notably high starting torque and controllability, have led to their application in a wide range of systems requiring accurate control of speed and position. This process has been helped by the development of sophisticated modern drive and computer control systems.

### Principles

It is well known that when a current-carrying conductor is placed in a magnetic field, it experiences a force (Fig. 1.22).

*Fig. 1.22 Force on a conductor in a magnetic field*



The force acting on the conductor is given by:

$$F = I \times B$$

where B = magnetic flux density and I = current

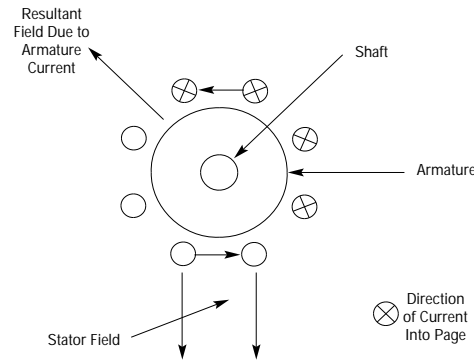
If this single conductor is replaced by a large number of conductors (i.e., a length of wire is wound into a coil), the force per unit length is increased by the number of turns in the coil. This is the basis of a DC motor.

### Practical Considerations

The problem now is that of using this force to produce the continuous torque required in a practical motor.

To achieve maximum performance from the motor, the maximum number of conductors must be placed in the magnetic field, to obtain the greatest possible force. In practice, this produces a cylinder of wire, with the windings running parallel to the axis of the cylinder. A shaft is placed down this axis to act as a pivot, and this arrangement is called the motor armature (Fig. 1.23).

*Fig. 1.23 DC motor armature*

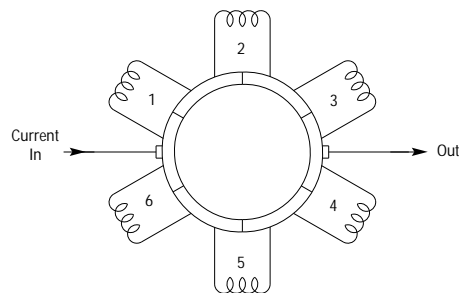


As the armature rotates, so does the resultant magnetic field. The armature will come to rest with its resultant field aligned with that of the stator field, unless some provision is made to constantly change the direction of the current in the individual armature coils.

### Commutation

The force that rotates the motor armature is the result of the interaction between two magnetic fields (the stator field and the armature field). To produce a constant torque from the motor, these two fields must remain constant in magnitude and in relative orientation.

*Fig. 1.24 Electrical arrangement of the armature*



This is achieved by constructing the armature as a series of small sections connected in sequence to the segments of a commutator (Fig 1.24). Electrical connection is made to the commutator by means of two brushes. It can be seen that if the armature rotates through 1/6 of a revolution clockwise, the current in coils 3 and 6 will have changed direction. As successive commutator segments pass the brushes, the current in the coils connected to those segments changes direction. This commutation or switching effect results in a current flow in the

armature that occupies a fixed position in space, independent of the armature rotation, and allows the armature to be regarded as a wound core with an axis of magnetization fixed in space. This gives rise to the production of a constant torque output from the motor shaft.

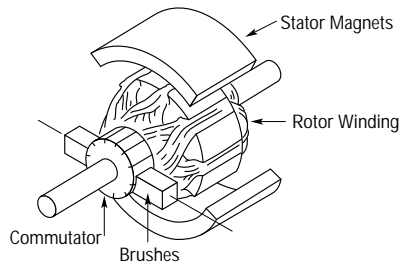
The axis of magnetization is determined by the position of the brushes. If the motor is to have similar characteristics in both directions of rotation, the brush axis must be positioned to produce an axis of magnetization that is at 90° to the stator field.

## DC Motor Types

Several different types of DC motor are currently in use.

**Iron cored.** (Fig. 1.25). This is the most common type of motor used in DC servo systems. It is made up of two main parts; a housing containing the field magnets and a rotor made up of coils of wire wound in slots in an iron core and connected to a commutator. Brushes, in contact with the commutator, carry current to the coils.

Fig. 1.25 Iron-cored motor



**Moving coil.** There are two principle forms of this type of motor. 1. The "printed" motor (Fig. 1.26), using a disc armature. 2. The "shell" type armature (Fig. 1.27).

Since these types of motors have no moving iron in their magnetic field, they do not suffer from iron losses. Consequently, higher rotational speeds can be obtained with low power inputs.

Fig. 1.26 Disc-armature "printed" motor

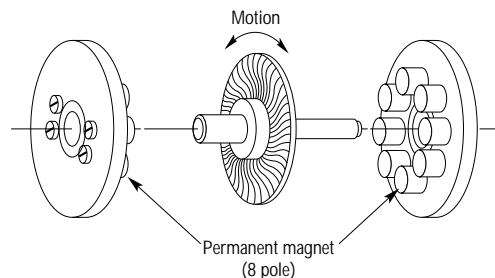
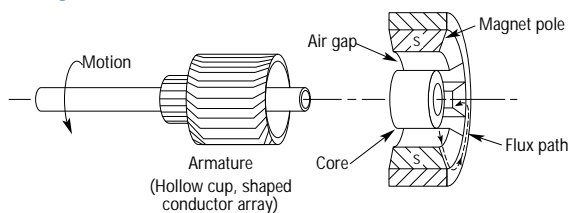


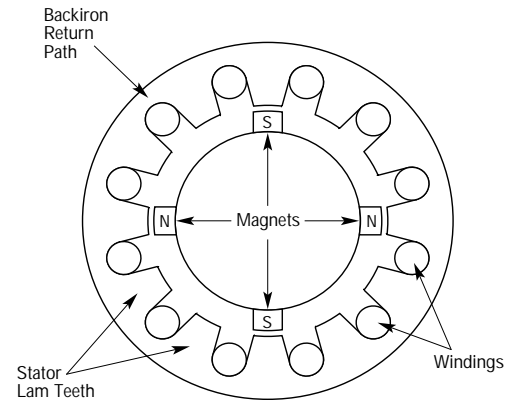
Fig. 1.27 Shell-armature motor



Diagrams courtesy of Electro-Craft Ltd.

**Brushless.** The major limiting factor in the performance of iron-cored motors is internal heating. This heat escapes through the shaft and bearings to the outer casing, or through the air gap between the armature and field magnets and from there to the casing. Both of these routes are thermally inefficient, so cooling of the motor armature is very poor.

Fig. 1.28 Brushless motor



In the brushless motor, the construction of the iron cored motor is turned inside out, so that the rotor becomes a permanent magnet and the stator becomes a wound iron core.

The current-carrying coils are now located in the housing, providing a short, efficient thermal path to the outside air. Cooling can further be improved by finning the outer casing and blowing air over it if necessary (to effectively cool an iron-cored motor, it is necessary to blow air through it.) The ease of cooling the brushless motor allows it to produce a much higher power in relation to its size.

The other major advantage of brushless motors is their lack of a conventional commutator and brush gear. These items are a source of wear and potential trouble and may require frequent maintenance. By not having these components, the brushless motor is inherently more reliable and can be used in adverse environmental conditions.

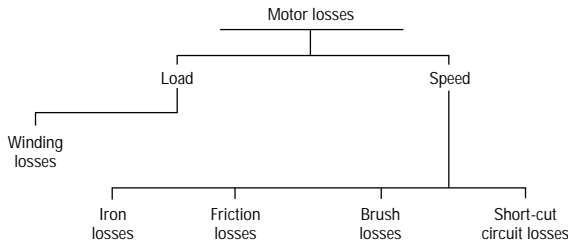
To achieve high torque and low inertia, brushless motors do require rare earth magnets that are much more expensive than conventional ceramic magnets. The electronics necessary to drive a brushless motor are also more complex than for a brush motor. A more thorough explanation of brushless motors is provided on page A17.

## Losses in DC Motors

DC motors are designed to convert electrical power into mechanical power and as a consequence of this, during periods of deceleration or if externally driven, will generate electrical power. However, all the input power is not converted into mechanical power due to the electrical resistance of the armature and other rotational losses. These losses give rise to heat generation within the motor.

Motor losses can be divided into two areas: Those that depend on the load and those that depend on speed (Fig. 1.29).

*Fig. 1.29 Losses in a DC motor*



**Winding losses.** These are caused by the electrical resistance of the motor windings and are equal to  $I^2R$  (where  $I$  = armature current and  $R$  = armature resistance).

As the torque output of the motor increases,  $I$  increases, which gives rise to additional losses. Consideration of winding losses is very important since heating of the armature winding causes an increase in  $R$ , which results in further losses and heating. This process can destroy the motor if the maximum current is not limited. Furthermore, at higher temperatures, the field magnets begin to lose their strength. Hence, for a required torque output the current requirement becomes greater.

**Brush contact losses.** These are fairly complex to analyze since they depend upon several factors that will vary with motor operation. In general, brush contact resistance may represent a high proportion of the terminal resistance of the motor. The result of this resistance will be increased heating due to  $I^2R$  losses in the brushes and contact area.

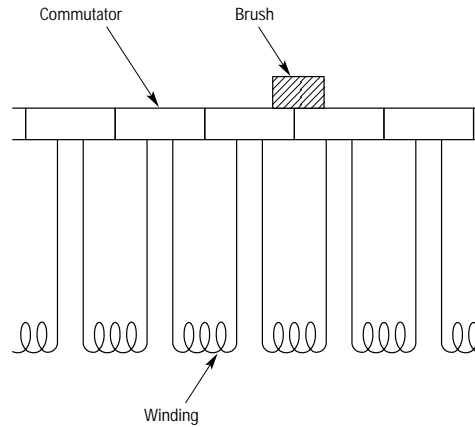
**Iron losses.** Iron losses are the major factor in determining the maximum speed that may be attained by an iron-cored motor. These fall into two categories:

- Eddy current losses are common in all conductive cored components experiencing a changing magnetic field. Eddy currents are induced into the motor armature as it undergoes changes in magnetization. These currents are speed-dependent and have a significant heating effect at high speeds. In practice, eddy currents are reduced by producing the armature core as a series of thin, insulated sections or laminations, stacked to produce the required core length.
- Hysteresis losses are caused by the resistance of the core material to constant changes of magnetic orientation, giving rise to additional heat generation, which increases with speed.

**Friction losses.** These are associated with the mechanical characteristics of the motor and arise from brush friction, bearing friction, and air resistance. These variables will generate heat and will require additional armature current to offset this condition.

**Short circuit currents.** As the brushes slide over the commutator, the brush is in contact with two commutator segments for a brief period. During this period, the brush will short out the coil connected to those segments (Fig. 1.30). This condition generates a torque that opposes the main driving torque and increases with motor speed.

*Fig. 1.30 Generation of short-circuit currents*

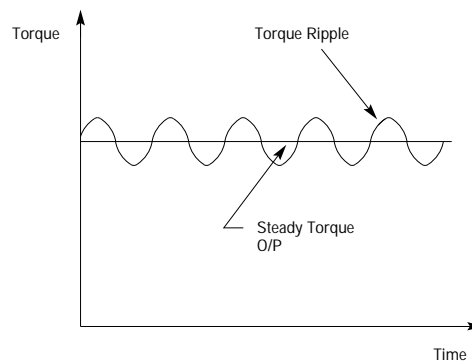


All these losses will contribute heat to the motor and it is this heating that will ultimately limit the motor application.

### Other Limiting Considerations

**Torque ripple.** The requirement for constant torque output from a DC motor is that the magnetic fields due to the stator and the armature are constant in magnitude and relative orientation, but this ideal is not achieved in practice. As the armature rotates, the relative orientation of the fields will change slightly and this will result in small changes in torque output called "torque ripple" (Fig. 1.31).

*Fig. 1.31 Torque ripple components*



This will not usually cause problems at high speeds since the inertia of the motor and the load will tend to smooth out the effects, but problems may arise at low speeds.

Motors can be designed to minimize the effects of torque ripple by increasing the number of windings, or the number of motor poles, or by skewing the armature windings.

**Demagnetization.** The permanent magnets of a DC motor field will tend to become demagnetized whenever a current flows in the motor armature. This effect is known as “armature reaction” and will have a negligible effect in normal use. Under high load conditions, however, when motor current may be high, the effect will cause a reduction in the torque constant of the motor and a consequent reduction in torque output.

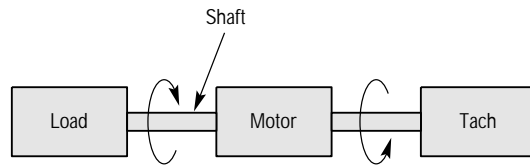
Above a certain level of armature current, the field magnets will become permanently demagnetized. Therefore, it is important not to exceed the maximum pulse current rating for the motor.

**Mechanical resonances and backlash.** It might normally be assumed that a motor and its load, including a tachometer or position encoder, are all rigidly connected together. This may, however, not be the case.

It is important for a bi-directional drive or positioning system that the mechanics are free from backlash, otherwise, true positioning will present problems.

In high-performance systems, with high accelerations, interconnecting shafts and couplings may deflect under the applied torque, such that the various parts of the system may have different instantaneous velocities that may be in opposite directions. Under certain conditions, a shaft may go into *torsional resonance* (Fig. 1.32).

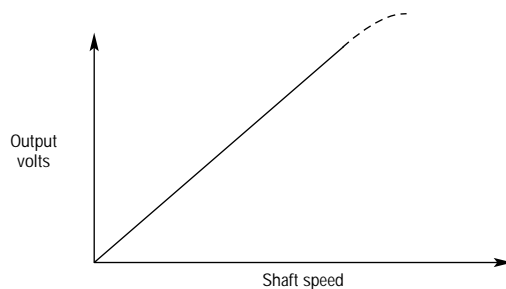
Fig. 1.32 Torsional oscillation



### Back emf

As described previously, a permanent magnet DC motor will operate as a generator. As the shaft is rotated, a voltage will appear across the brush terminals. This voltage is called the *back electromotive force* (emf) and is generated even when the motor is driven by an applied voltage. The output voltage is essentially linear with motor speed and has a slope that is defined as the motor voltage constant,  $K_E$  (Fig. 1.33).  $K_E$  is typically quoted in volts per 1000 rpm.

Fig. 1.33 Back-emf characteristic



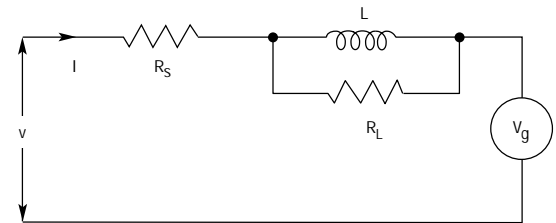
### Motor Equations

Unlike a step motor, the DC brush motor exhibits simple relationships between current, voltage, torque and speed. It is therefore worth examining these relationships as an aid to the application of brush motors.

The application of a constant voltage to the terminals of a motor will result in its accelerating to attain a steady final speed ( $n$ ). Under these conditions, the voltage ( $V$ ) applied to the motor is opposed by the back emf ( $nK_E$ ) and the resultant voltage drives the motor current ( $I$ ) through the motor armature and brush resistance ( $R_s$ ).

The equivalent circuit of a DC motor is shown in Fig. 1.34.

Fig. 1.34 DC motor equivalent circuit



$R_s$  = motor resistance

$L$  = winding inductance

$V_g$  = back emf and

$R_L$  represents magnetic losses.

The value of  $R_L$  is usually large and so can be ignored, as can the inductance  $L$ , which is generally small.

If we apply a voltage ( $V$ ) to the motor and a current ( $I$ ) flows, then:

$$V = IR_s + V_g$$

but  $V_g = nK_E$

$$\text{so } V = IR_s + nK_E \quad (1)$$

This is the electrical equation of the motor.

If  $K_T$  is the torque constant of the motor (typically in oz/in per Amp), then the torque generated by the motor is given by:

$$T = IK_T \quad (2)$$

The opposing torque due to friction ( $T_f$ ) and viscous damping ( $K_D$ ) is given by:

$$T_M = T_f + nK_D$$

If the motor is coupled to a load  $T_L$ , then at constant speed:

$$T = T_L + T_f + nK_D \quad (3)$$

Equations (1), (2) and (3) allow us to calculate the required current and drive voltage to meet given torque and speed requirements. The values of  $K_T$ ,  $K_E$ , etc. are given in the motor manufacturer's data.