

EE 1291

Energy Conversion and Transport

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Chapter 3 **DC Motors**

3.1 DC Motor

- **The direct current (dc) machine can be used as a motor or as a generator.**
- **DC Machine is most often used for a motor.**
- **The major advantages of dc machines are the easy speed and torque regulation.**
- **However, their application is limited to mills, mines and trains. As examples, trolleys and underground subway cars may use dc motors.**
- **In the past, automobiles were equipped with dc dynamos to charge their batteries.**

3.1 DC Motor

- **Even today the starter is a series dc motor**
- **However, the recent development of power electronics has reduced the use of dc motors and generators.**
- **The electronically controlled ac drives are gradually replacing the dc motor drives in factories.**
- **Nevertheless, a large number of dc motors are still used by industry and several thousand are sold annually.**

Construction

DC Machine Construction

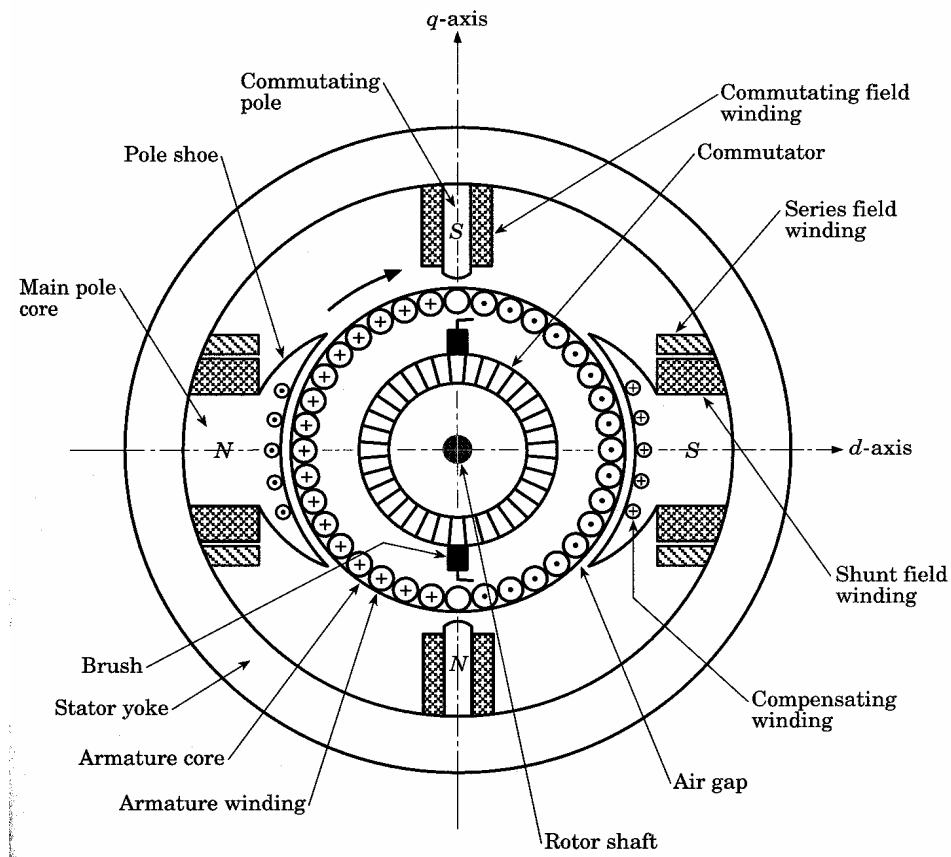
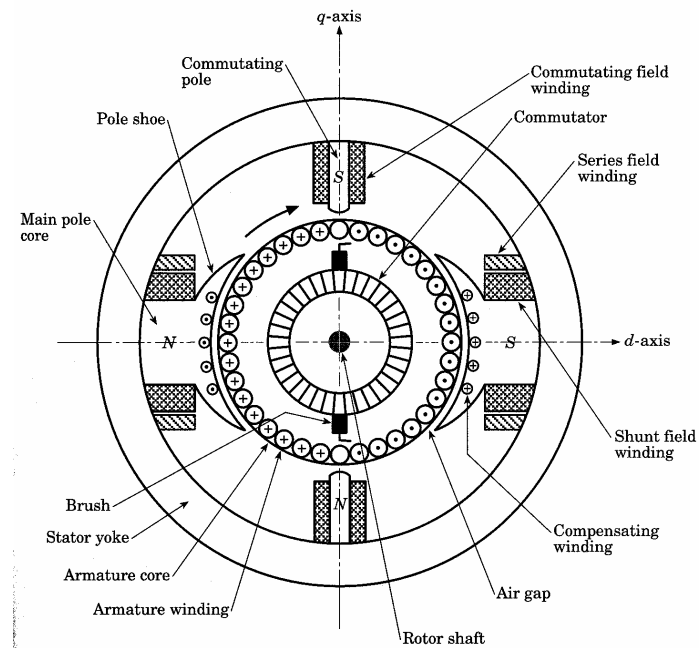


Figure 8.1 General arrangement of a dc machine

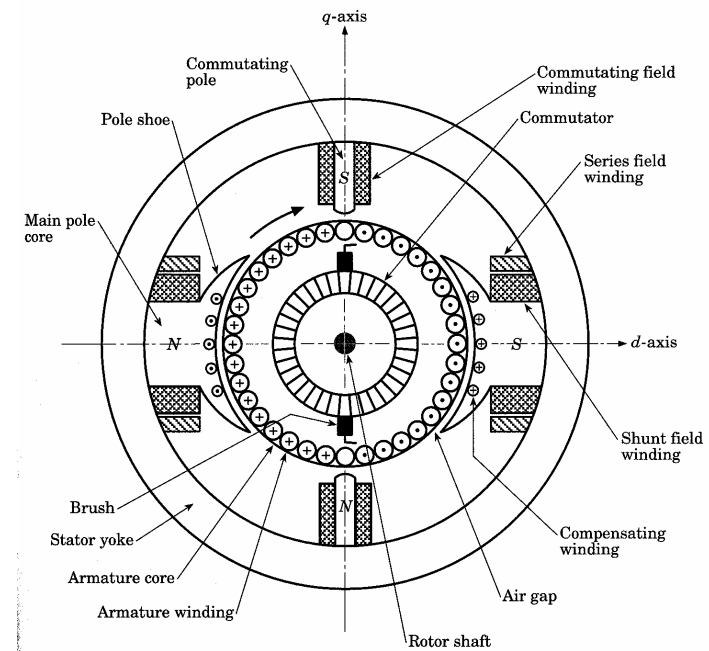
DC Machines

- The stator of the dc motor has poles, which are excited by dc current to produce magnetic fields.
- In the neutral zone, in the middle between the poles, commutating poles are placed to reduce sparking of the commutator. The commutating poles are supplied by dc current.
- **Compensating windings are mounted on the main poles. These short-circuited windings damp rotor oscillations.**



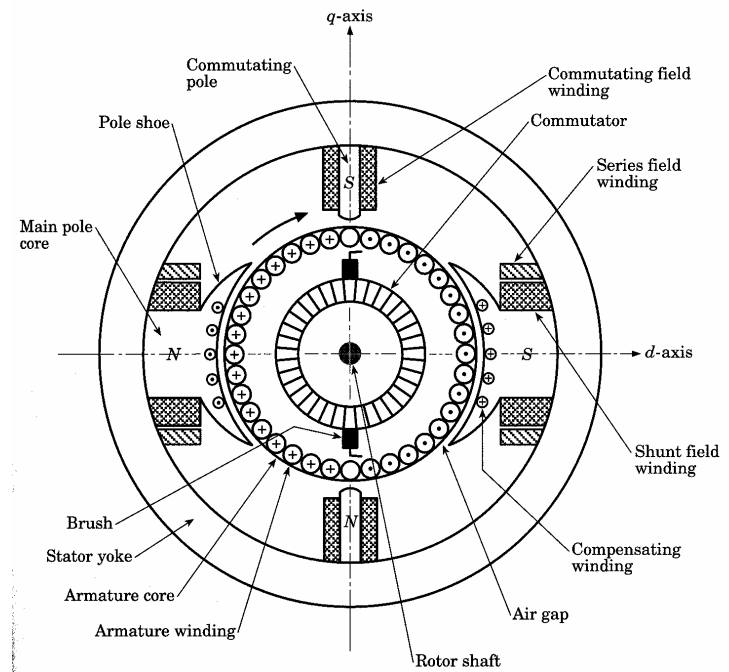
DC Machines

- The poles are mounted on an iron core that provides a closed magnetic circuit.
- The motor housing supports the iron core, the brushes and the bearings.
- The rotor has a ring-shaped laminated iron core with slots.
- Coils with several turns are placed in the slots. The distance between the two legs of the coil is about 180 electric degrees.



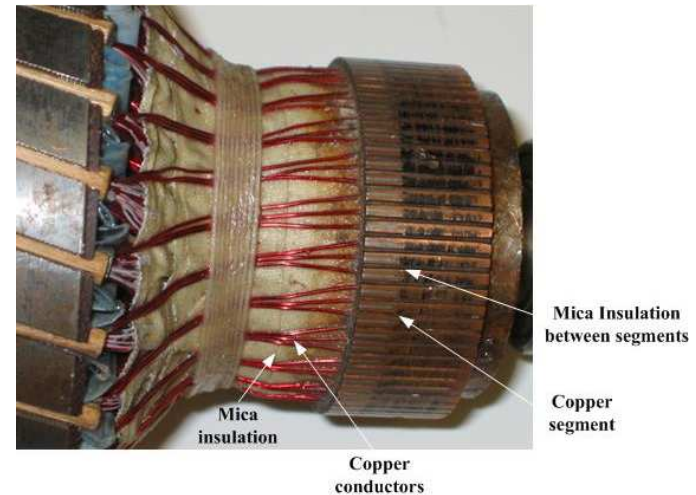
DC Machines

- **The coils are connected in series through the commutator segments.**
- **The ends of each coil are connected to a commutator segment.**
- **The commutator consists of insulated copper segments mounted on an insulated tube.**
- **Two brushes are pressed to the commutator to permit current flow.**
- **The brushes are placed in the neutral zone, where the magnetic field is close to zero, to reduce arcing.**



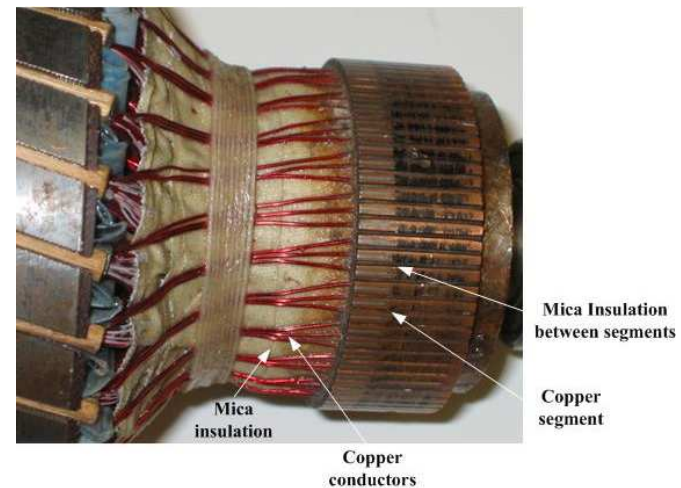
DC Machines

- The rotor has a ring-shaped laminated iron core with slots.
- The commutator consists of insulated copper segments mounted on an insulated tube.
- Two brushes are pressed to the commutator to permit current flow.
- The brushes are placed in the neutral zone, where the magnetic field is close to zero, to reduce arcing.



DC Machines

- The *commutator* switches the current from one rotor coil to the adjacent coil,
- The switching requires the interruption of the coil current.
- The sudden interruption of an inductive current generates high voltages .
- The high voltage produces flashover and arcing between the commutator segment and the brush.



DC Machine Construction

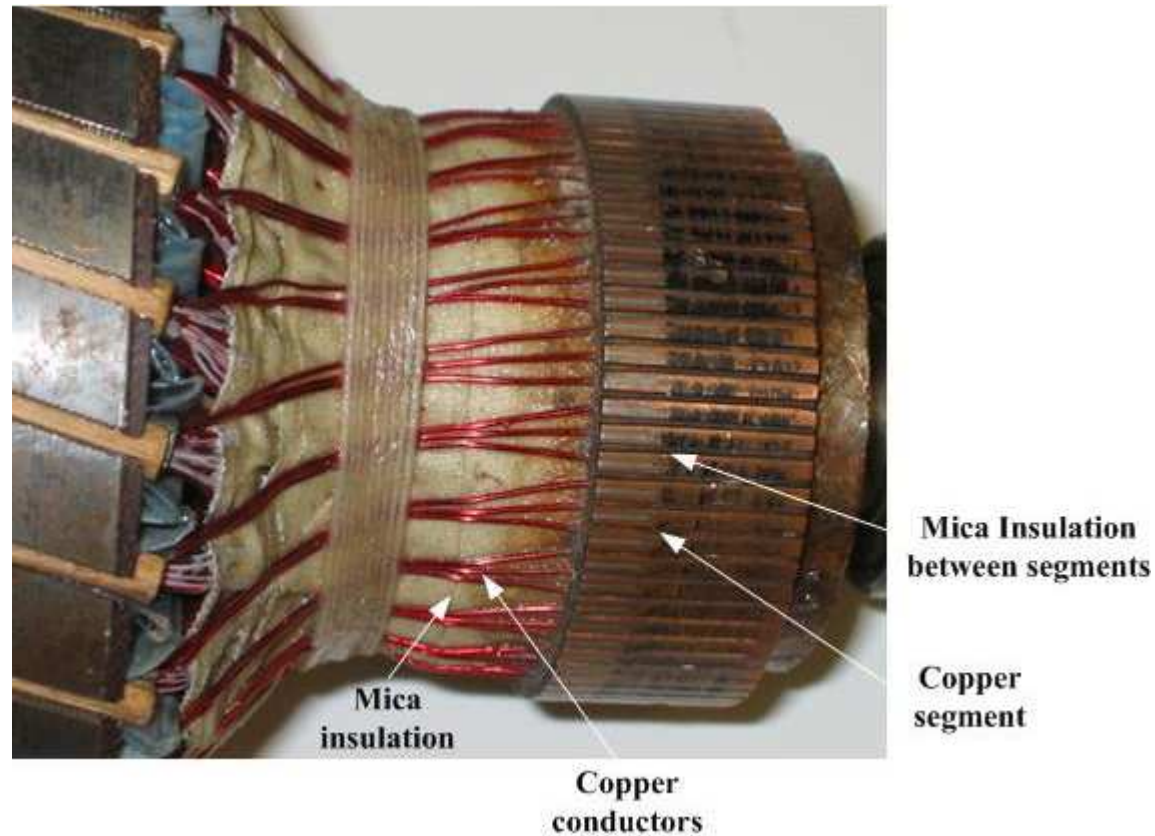


Figure 8.3 Details of the commutator of a dc motor.

DC Machine Construction

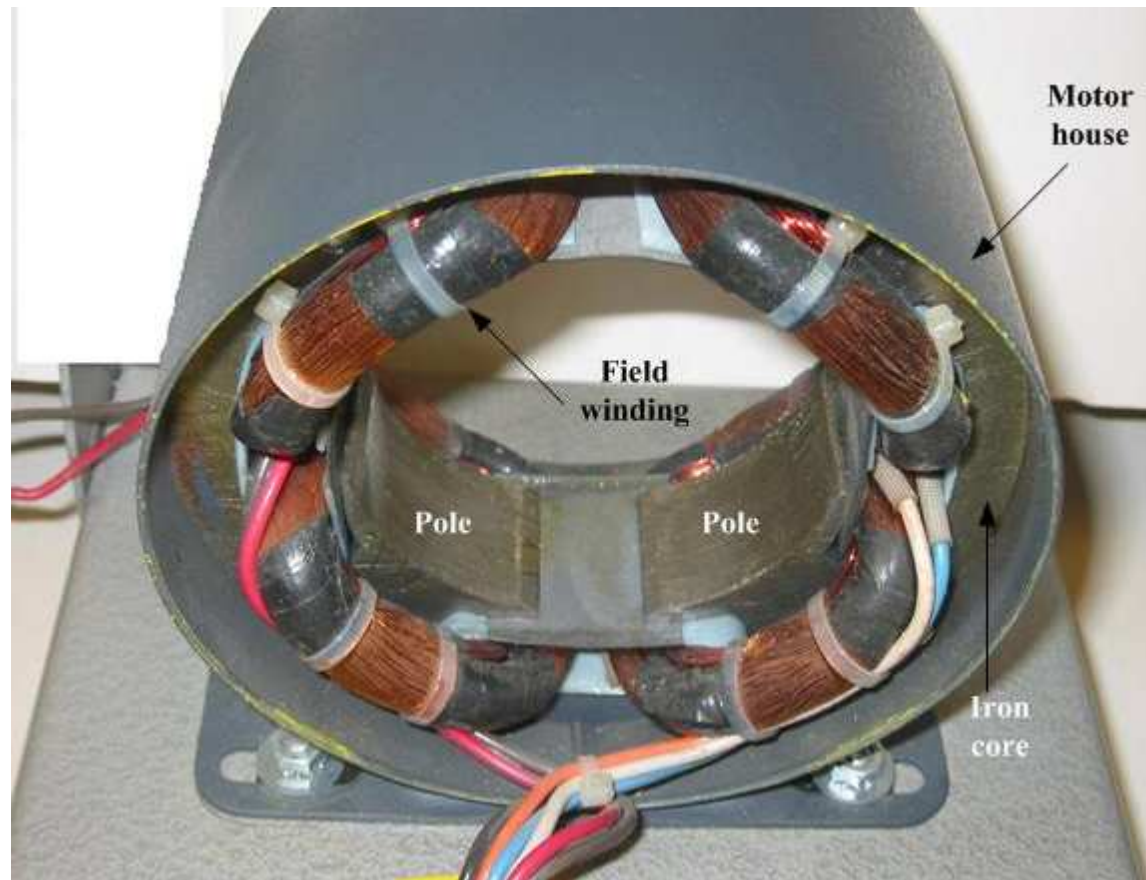


Figure 8.4 DC motor stator with poles visible.

DC Machine Construction

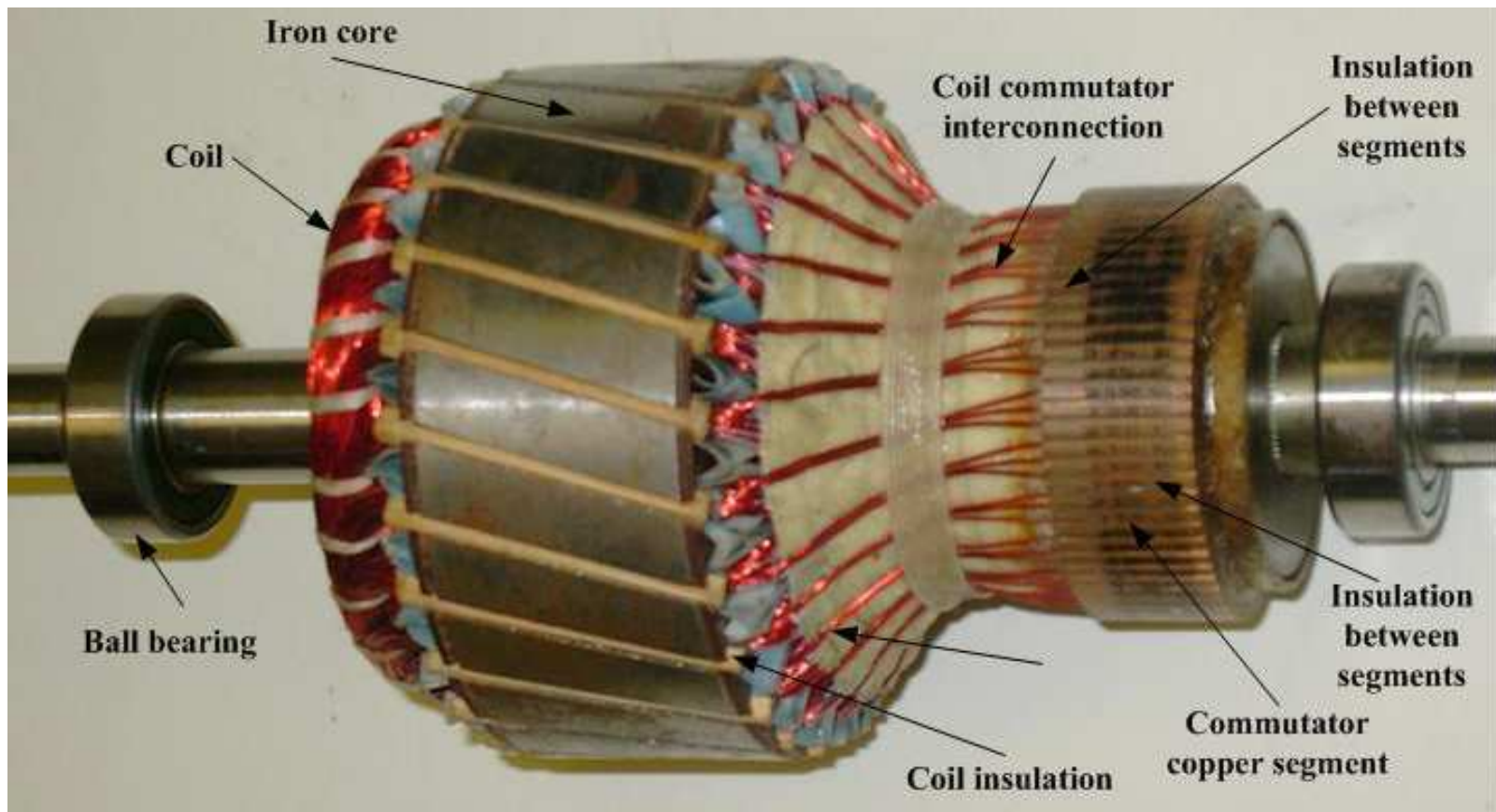


Figure 8.5 Rotor of a dc motor.

DC Machine Construction

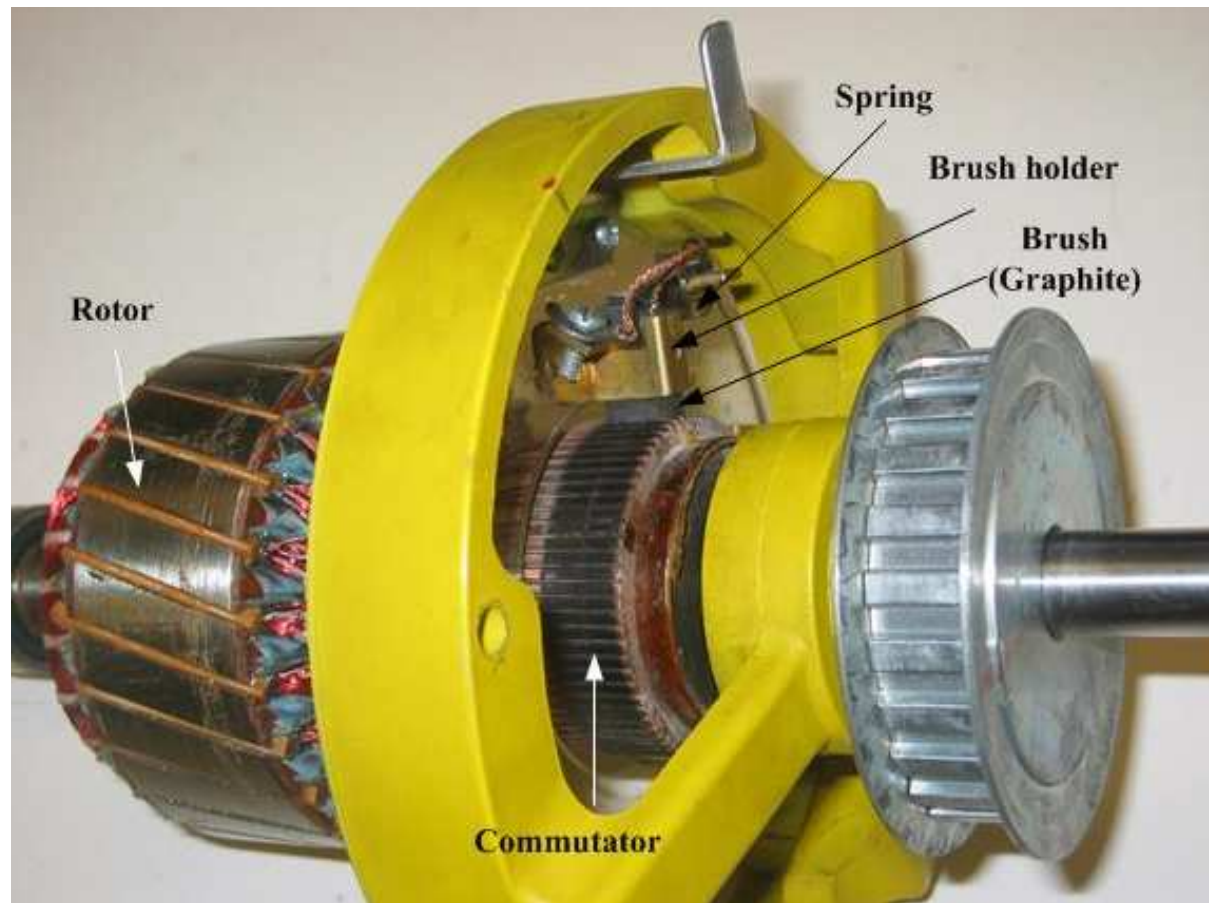
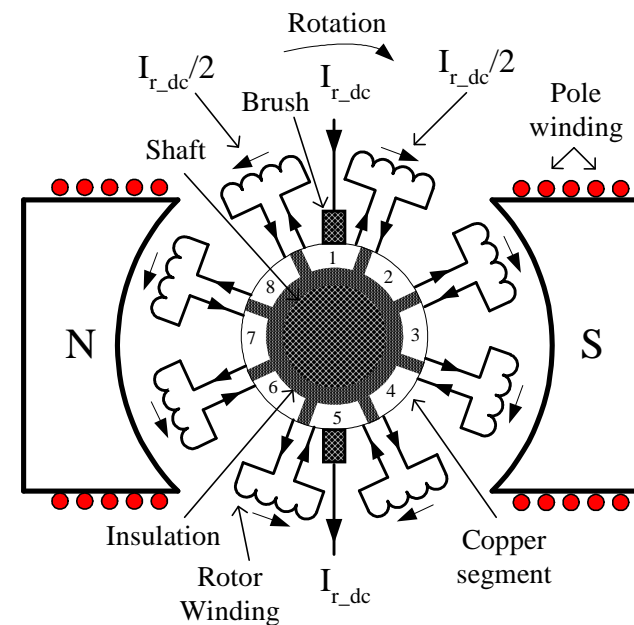


Figure 8.6 Cutaway view of a dc motor.

DC Motor Operation

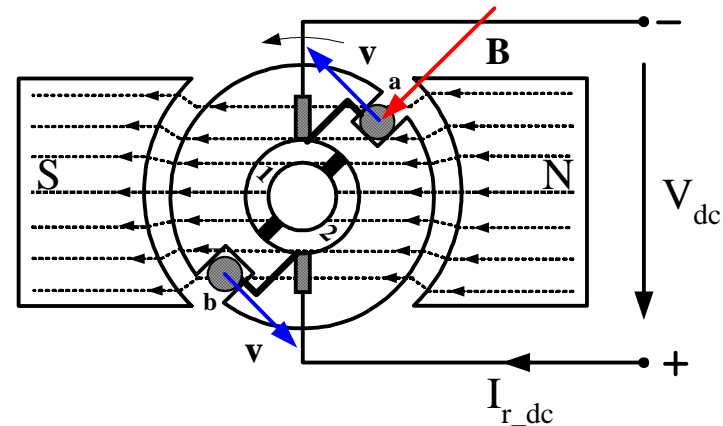
DC Motor Operation

- In a dc motor, the stator poles are supplied by dc excitation current, which produces a dc magnetic field.
- The rotor is supplied by dc current through the brushes, commutator and coils.
- The interaction of the magnetic field and rotor current generates a force that drives the motor

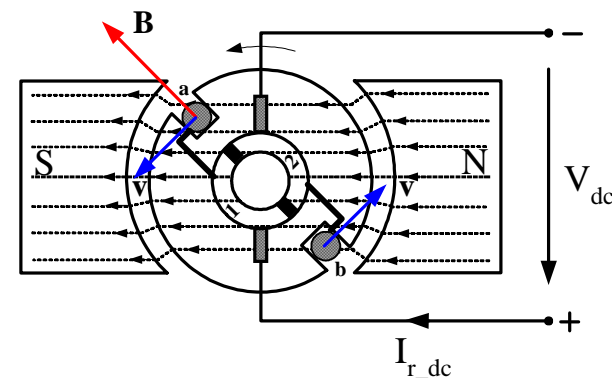


DC Motor Operation

- The magnetic field lines enter into the rotor from the north pole (N) and exit toward the south pole (S).
- The poles generate a magnetic field that is perpendicular to the current carrying conductors.
- The interaction between the field and the current produces a Lorentz force,
- The force is perpendicular to both the magnetic field and conductor



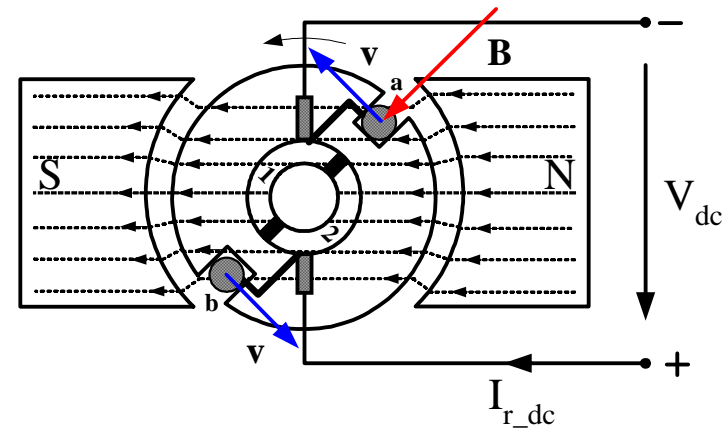
(a) Rotor current flow from segment 1 to 2 (slot a to b)



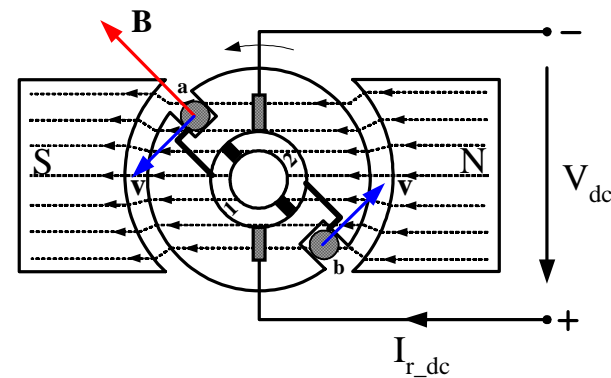
(b) Rotor current flow from segment 2 to 1 (slot b to a)

DC Motor Operation

- The generated force turns the rotor until the coil reaches the neutral point between the poles.
- At this point, the magnetic field becomes practically zero together with the force.
- However, inertia drives the motor beyond the neutral zone where the direction of the magnetic field reverses.
- To avoid the reversal of the force direction, the commutator changes the current direction, which maintains the counterclockwise rotation.



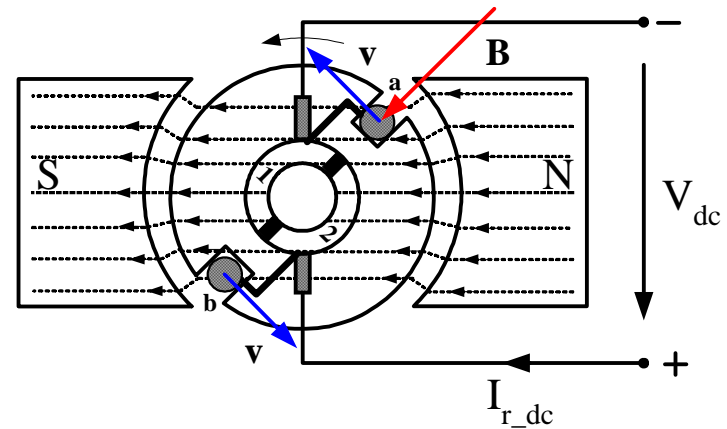
(a) Rotor current flow from segment 1 to 2 (slot **a** to **b**)



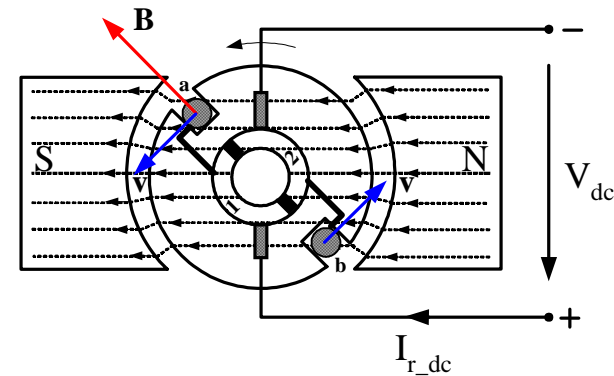
(b) Rotor current flow from segment 2 to 1 (slot **b** to **a**)

DC Motor Operation

- Before reaching the neutral zone, the current enters in segment 1 and exits from segment 2,
- Therefore, current enters the coil end at slot **a** and exits from slot **b** during this stage.
- After passing the neutral zone, the current enters segment 2 and exits from segment 1,
- This reverses the current direction through the rotor coil, when the coil passes the neutral zone.
- The result of this current reversal is the maintenance of the rotation.



(a) Rotor current flow from segment 1 to 2 (slot **a** to **b**)

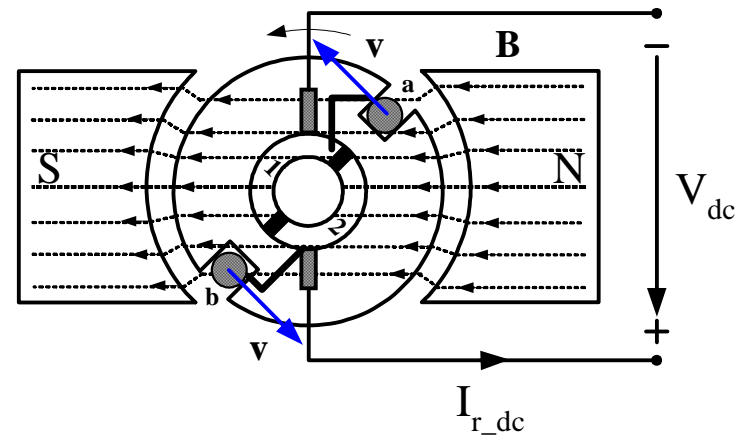


(b) Rotor current flow from segment 2 to 1 (slot **b** to **a**)

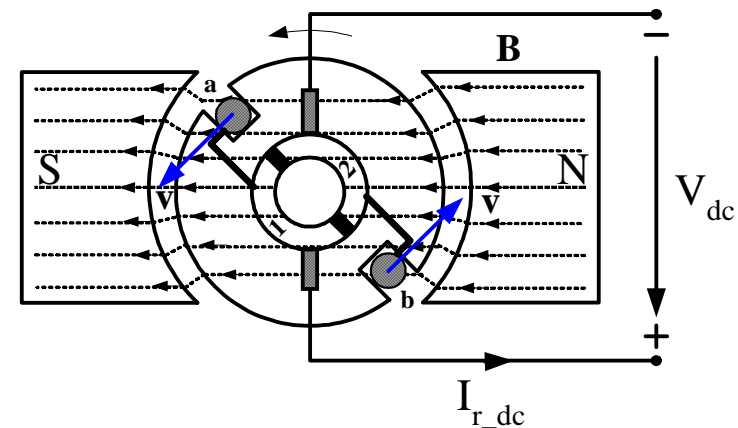
DC Generator Operation

DC Generator Operation

- **The N-S poles produce a dc magnetic field and the rotor coil turns in this field.**
- **A turbine or other machine drives the rotor.**
- **The conductors in the slots cut the magnetic flux lines, which induce voltage in the rotor coils.**
- **The coil has two sides: one is placed in slot a, the other in slot b.**



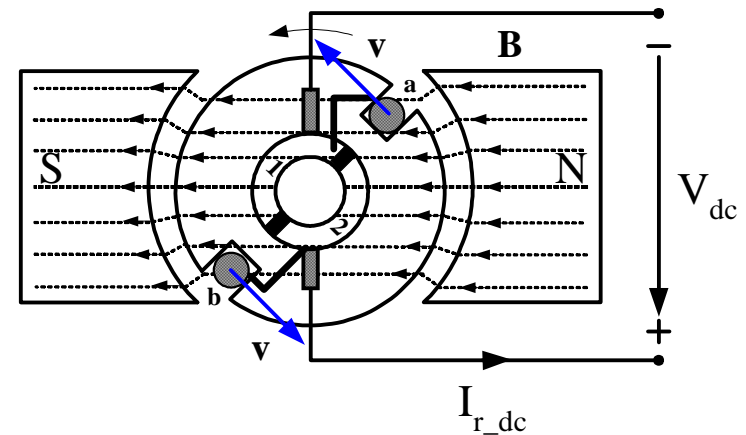
(a) Rotor current flow from segment 1 to 2 (slot a to b)



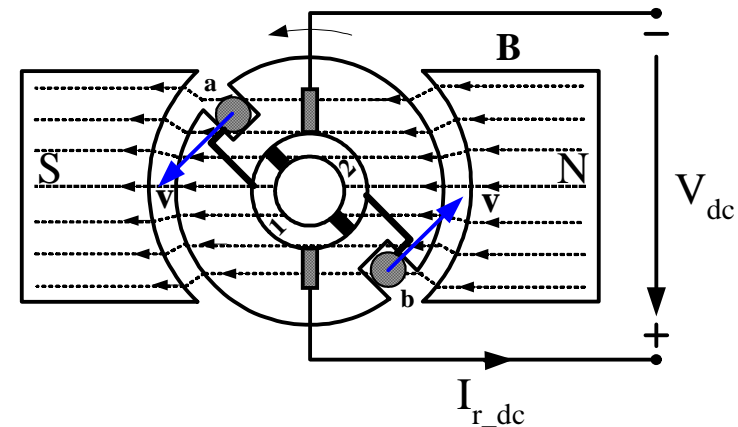
(b) Rotor current flow from segment 2 to 1 (slot b to a)

DC Generator Operation

- In Figure 8.11A, the conductors in slot a are cutting the field lines entering into the rotor from the north pole, from the north pole,
- The conductors in slot b are cutting the field lines exiting from the rotor to the south pole.
- The cutting of the field lines generates voltage in the conductors.
- The voltages generated in the two sides of the coil are added.



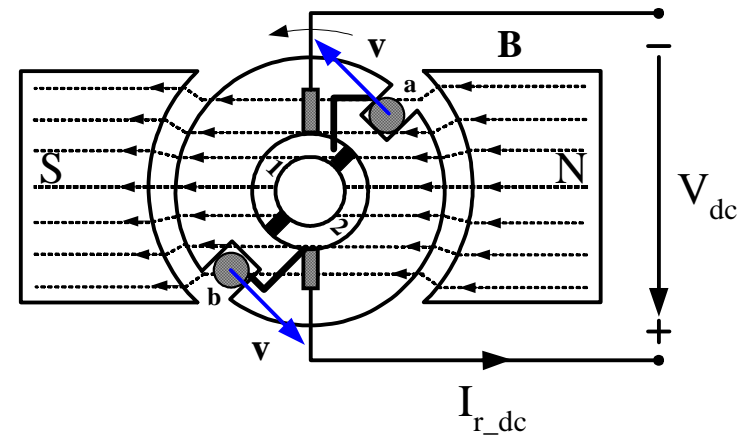
(a) Rotor current flow from segment 1 to 2 (slot a to b)



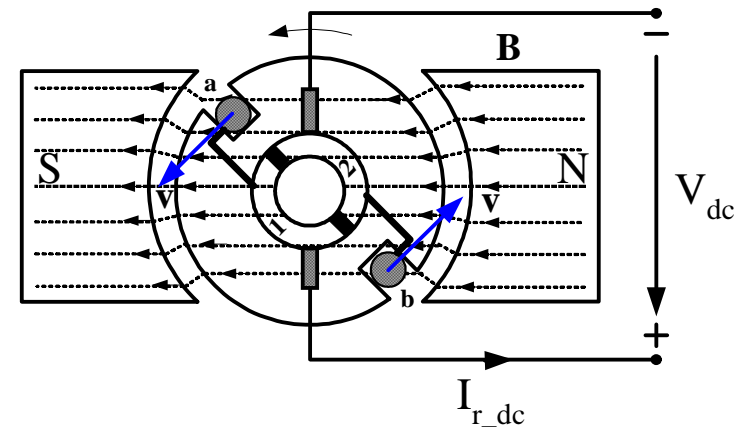
(b) Rotor current flow from segment 2 to 1 (slot b to a)

DC Generator Operation

- The induced voltage is connected to the generator terminals through the commutator and brushes.
- In Figure 8.11A, the induced voltage in **b** is positive, and in **a** is negative.
- The positive terminal is connected to commutator segment **2** and to the conductors in slot **b**.
- The negative terminal is connected to segment **1** and to the conductors in slot **a**.



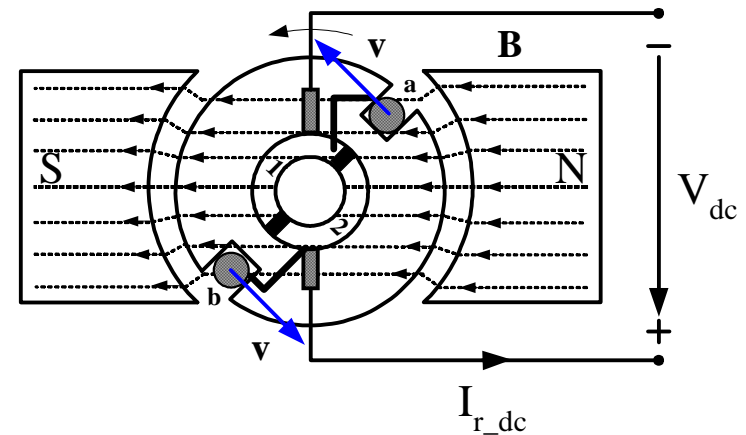
(a) Rotor current flow from segment 1 to 2 (slot **a** to **b**)



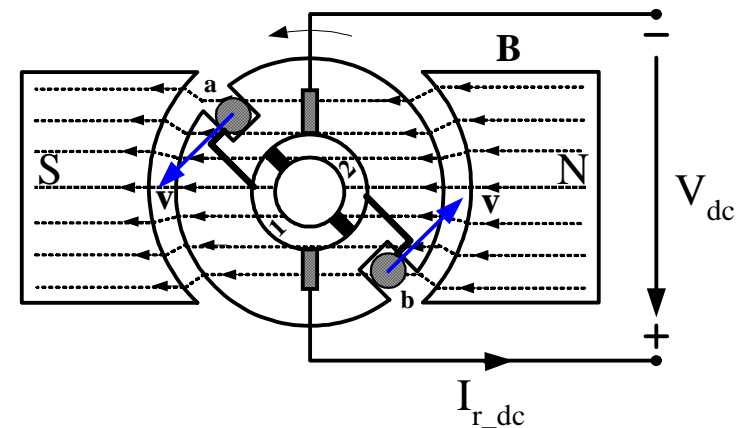
(b) Rotor current flow from segment 2 to 1 (slot **b** to **a**)

DC Generator Operation

- When the coil passes the neutral zone:
 - Conductors in slot **a** are then moving toward the south pole and cut flux lines exiting from the rotor
 - Conductors in slot **b** cut the flux lines entering the in slot **b**.
- This changes the polarity of the induced voltage in the coil.
- The voltage induced in **a** is now positive, and in **b** is negative.



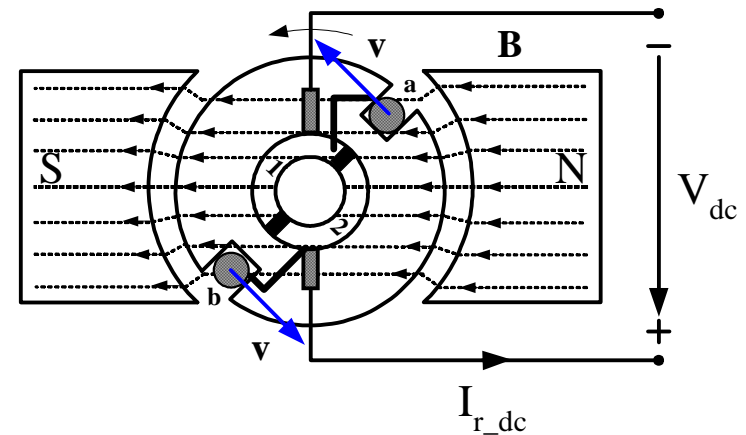
(a) Rotor current flow from segment 1 to 2 (slot **a** to **b**)



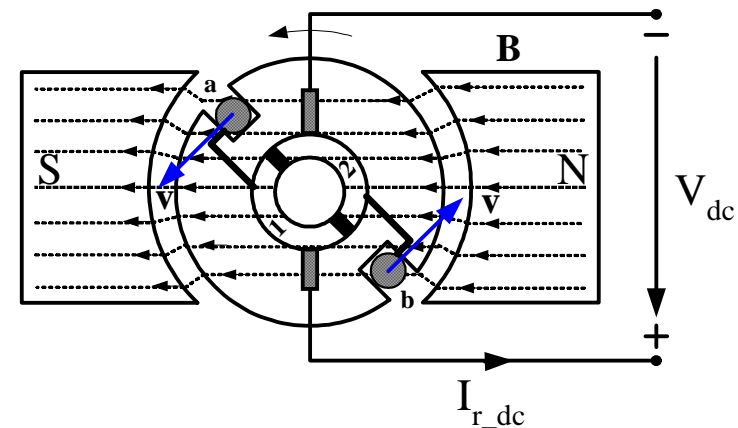
(b) Rotor current flow from segment 2 to 1 (slot **b** to **a**)

DC Generator Operation

- The simultaneously the commutator reverses its terminals, which assures that the output voltage (V_{dc}) polarity is unchanged.
- In Figure 8.11B
 - the positive terminal is connected to commutator segment 1 and to the conductors in slot a.
 - The negative terminal is connected to segment 2 and to the conductors in slot b.



(a) Rotor current flow from segment 1 to 2 (slot a to b)



(b) Rotor current flow from segment 2 to 1 (slot b to a)

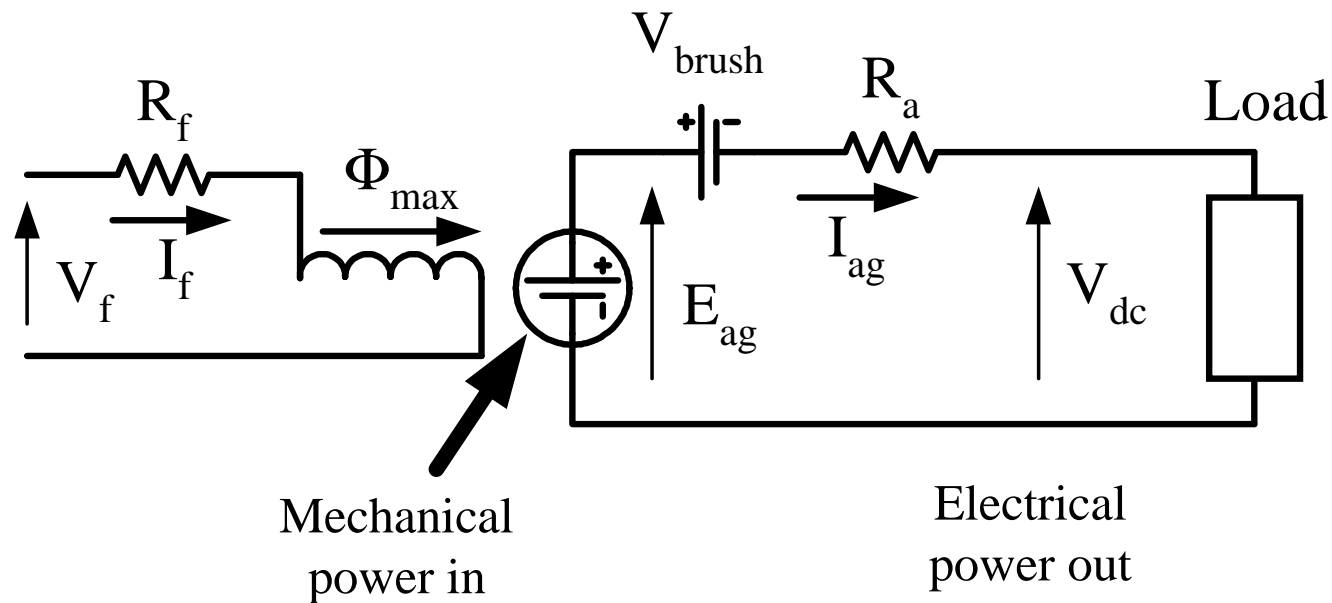
DC Machine Equivalent Circuit

Generator

DC Generator Equivalent circuit

- The magnetic field produced by the stator poles induces a voltage in the rotor (or armature) coils when the generator is rotated.
- This induced voltage is represented by a voltage source.
- The stator coil has resistance, which is connected in series.
- The pole flux is produced by the DC excitation/field current, which is magnetically coupled to the rotor
- The field circuit has resistance and a source
- The voltage drop on the brushes represented by a battery

DC Generator Equivalent circuit



- **Figure 8.12 Equivalent circuit of a separately excited dc generator.**

DC Generator Equivalent circuit

- The magnetic field produced by the stator poles induces a voltage in the rotor (or armature) coils when the generator is rotated.
- The dc field current of the poles generates a magnetic flux
- The flux is proportional with the field current if the iron core is not saturated:

$$\Phi_{ag} = K_1 I_f$$

DC Generator Equivalent circuit

- The rotor conductors cut the field lines that generate voltage in the coils.

$$E_{ag} = 2 N_r B \ell_g v$$

- The motor speed and flux equations are :

$$v = \omega \frac{D_g}{2} \quad \Phi_{ag} = B \ell_g D_g$$

DC Generator Equivalent circuit

- The combination of the three equations results in the induced voltage equation:

$$E_{ag} = 2 N_r B \ell_g v = 2 N_r B \ell_g \left(\omega \frac{D_g}{2} \right) = N_r (B \ell_g D_g) \omega = N_r \Phi_{ag} \omega$$

- The equation is simplified.

$$E_{ag} = N_r \Phi_{ag} \omega = N_r K_1 I_f \omega = K_m I_f \omega$$

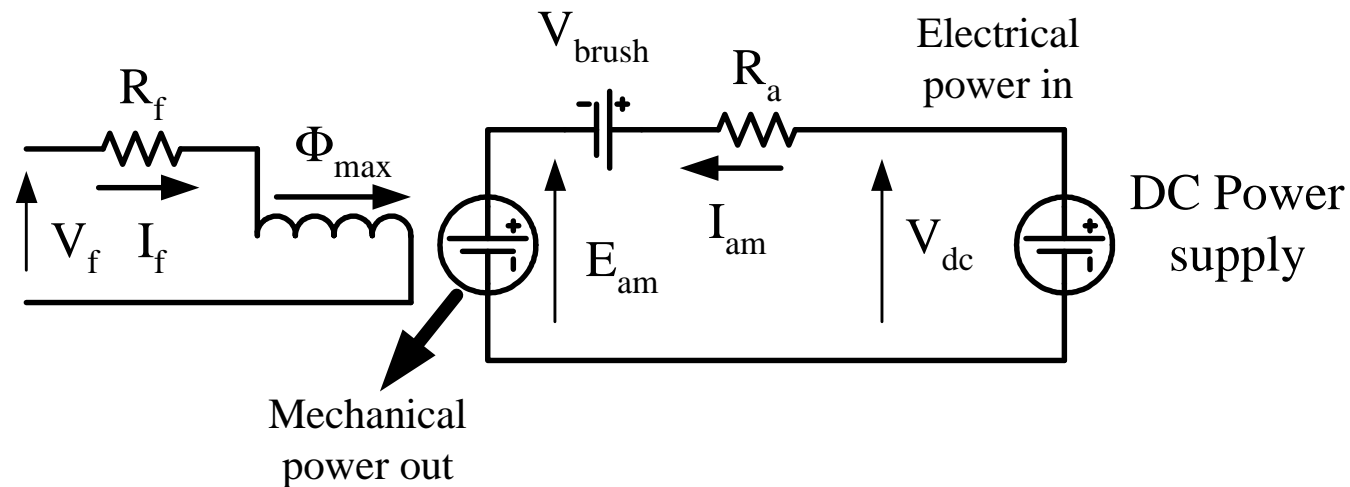
DC Generator Equivalent circuit

- When the generator is loaded, the load current produces a voltage drop on the rotor winding resistance.
- In addition, there is a more or less constant 1–3 V voltage drop on the brushes.
- These two voltage drops reduce the terminal voltage of the generator. The terminal voltage is;

$$E_{ag} = V_{dc} + I_{ag} R_a + V_{brush}$$

Motor

DC Motor Equivalent circuit



- **Figure 8.13** Equivalent circuit of a separately excited dc motor
- **Equivalent circuit is similar to the generator only the current directions are different**

DC Motor Equivalent circuit

- The operation equations are:
- Armature voltage equation

$$V_{dc} = E_{am} + I_{am} R_a + V_{brush}$$

The induced voltage and motor speed vs angular frequency

$$E_{am} = K_m I_f \omega \quad \omega = 2\pi n_m$$

DC Motor Equivalent circuit

- The operation equations are:
- The combination of the equations results in

$$K_m I_f \omega = E_{am} = V_{dc} - I_{am} R_m$$

The current is calculated from this equation. The output power and torque are:

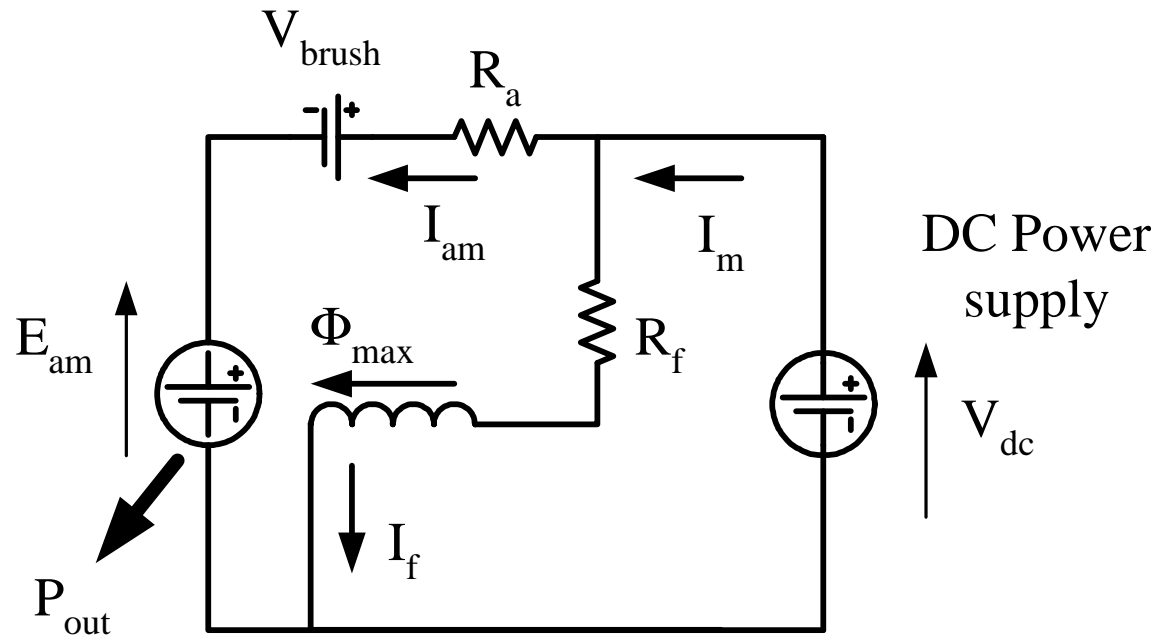
$$P_{out} = E_{am} I_{am} \quad T = \frac{P_{out}}{\omega} = K_m I_{am} I_f$$

DC Machine Excitation Methods

DC Motor Operation

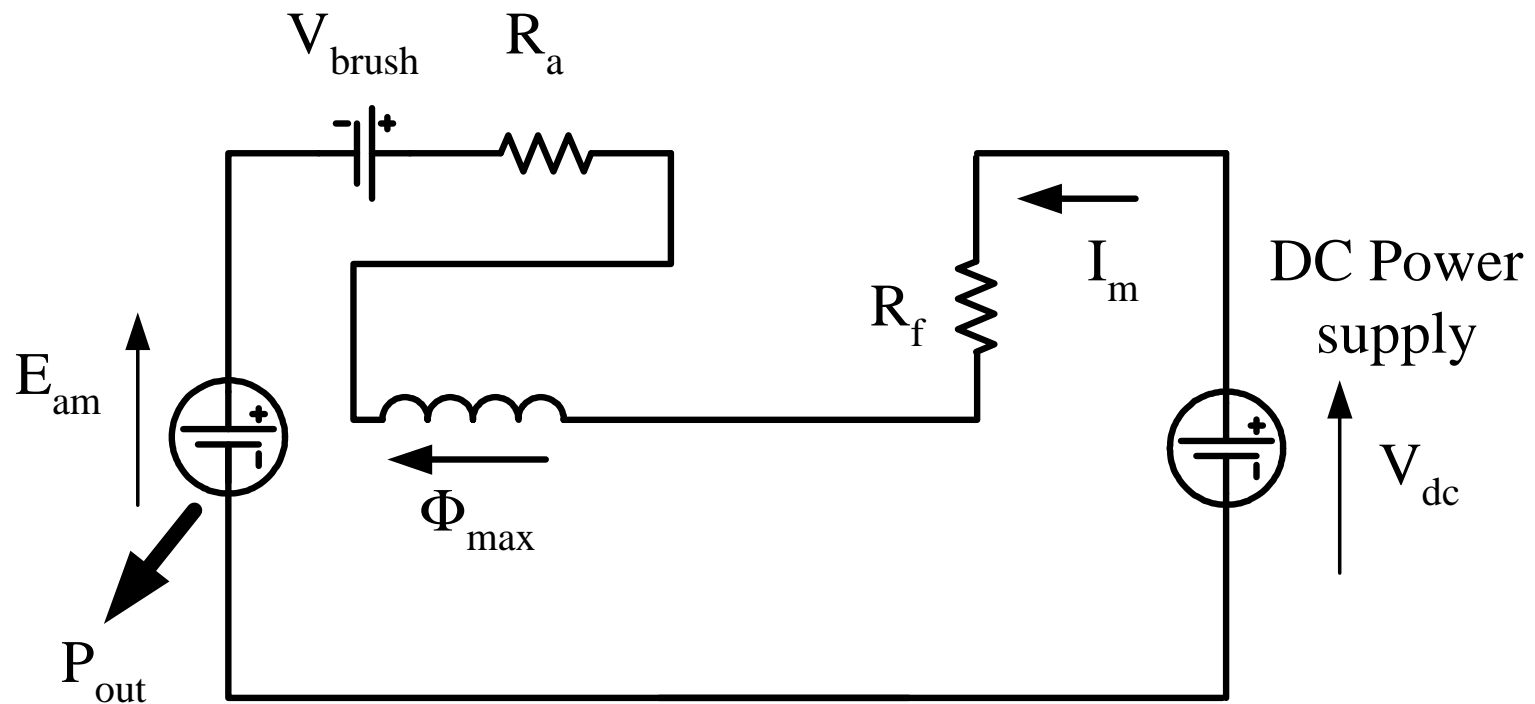
- **There are four different methods for supplying the dc current to the motor or generator poles:**
 - **Separate excitation;**
 - **Shunt connection**
 - **Series connection**
 - **Compound**

DC Motor Equivalent circuit



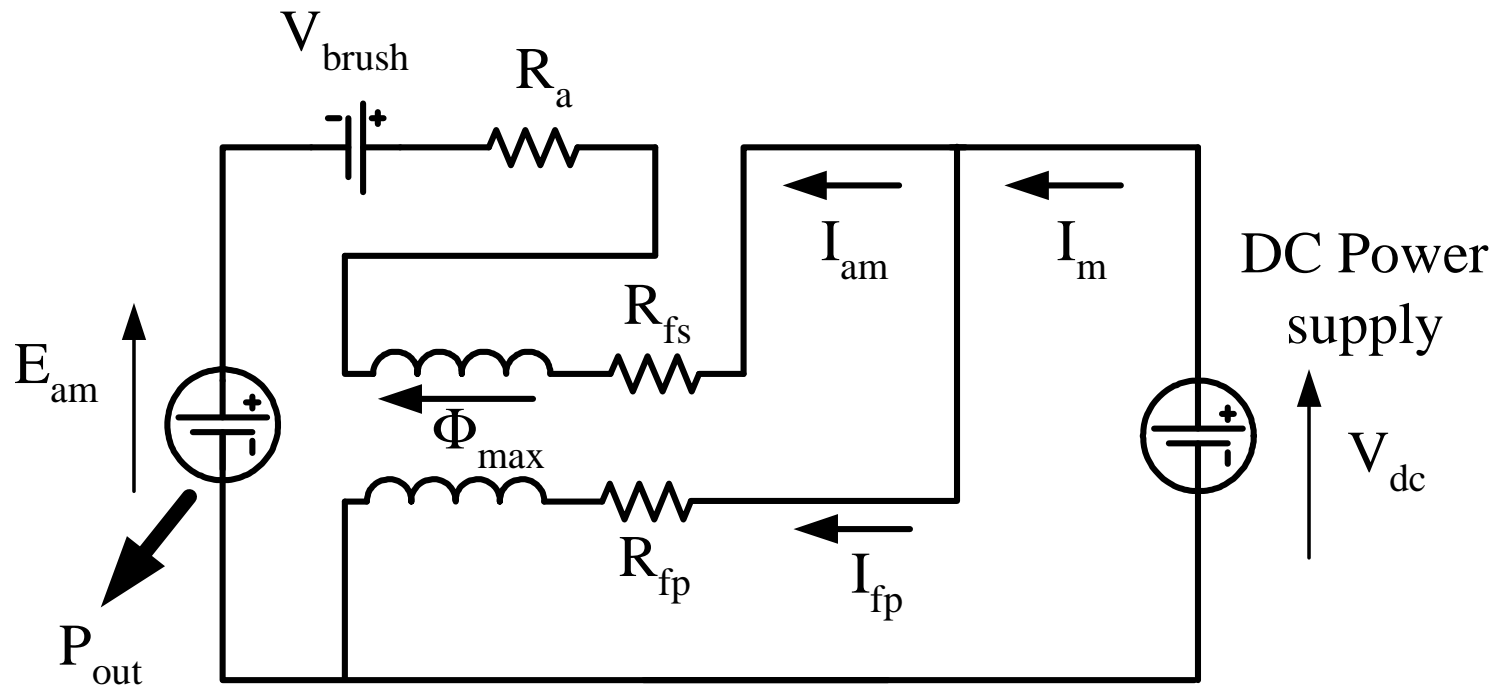
- **Figure 8.14** Equivalent circuit of a shunt dc motor

DC Motor Equivalent circuit



• **Figure 8.15** Equivalent circuit of a series dc motor

DC Motor Equivalent circuit



- Figure 8.16 Equivalent circuit of a compound dc motor