

# Chapter 7 – DC Machines

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## 7.1 Introduction

Dc machines have several unique characteristics. As with other machines, the dc device can be modeled as a Thevenin equivalent voltage and impedance with a magnetizing circuit consisting of an inductor with its resistance. The magnetizing circuit field can be dc or a permanent magnet. The Thevenin armature is dc.

The speed is controlled by varying the voltage and resulting flux on the field. Large dc machines originally were used because of this ability. However, these machines are largely replaced by induction machines with electronic frequency control.

Because of the dc, these machines are often very small so they can run from a battery. T

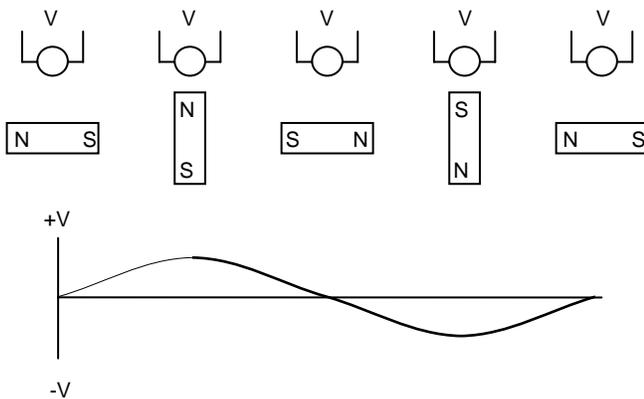
## 7.2 Application

Dc motors are predominant in very small, miniaturized systems since they can run from batteries. They were formerly used for larger machines because of the ease in adjusting voltage and as a result adjusting speed. However, most motors that are fractional horsepower or above are now induction machines. Frequency and resulting speed control is accomplished by electronic switching.

Dc motors are still common in transportation systems such as automobiles, trucks, and airplanes. With a DC power system, dc machines are logical. Dc motors now are used mostly in specialty applications. Dc generators are seldom employed.

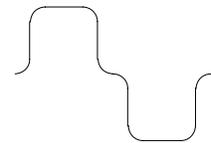
## 7.3 Universal motor

By definition, a rotating machine is cyclic in nature. Therefore, it is an alternating current device. Note the diagram from the alternating current chapter.



As a direct current machine, it would be expected that the output of the loop would be more like a square wave. The waveform has the square like characteristics except at the corners where a transition of voltage level or polarity occurs.

The process of converting an ac machine to a dc machine is called commutation. Commutation is simply conversion of alternating to unidirectional current. It involves the reversal of current direction. To change the current direction, the coil is switched either mechanically, by a relay, or by electronic switches as the machine rotates. The result is a waveform that is similar to a rounded-corner square-wave.



Dc motors are sometimes referred to as a universal motor. It can obviously be operated from a dc supply. It can operate from an ac supply if the signal is rectified. It can operate as a variable speed motor simply by controlling the voltage supplied with a simple silicon controlled rectifier.

The field is on the stator. It can be from a voltage supply. Often in smaller units, the field is a permanent magnet. The armature is on the rotor. A voltage must be supplied to the rotating coil.



On most machines, this is accomplished by brushes that ride on a rotor contact. The brushes are generally carbon and have about a 2 Volt drop. The contact surface is generally a copper plate. There are multiple of this plates connected to the rotor windings.

## 7.4 Commutation problems

Three major problems arise with the commutation process. Flux weakening and neutral plane shift are called armature reaction. Inductive kick is the third problem.

Armature reaction is a voltage effect. It is the back electromotive force (emf) from the self-excitation. The field winding creates a magnetic flux to energize the air gap. Similarly the armature is a winding that has voltage applied. Therefore, the armature also creates a magnetic flux. The opposition of the field and armature flux creates a back emf or voltage that opposes the voltage induced on the armature. The effect is exactly the same as the repelling effect as two magnets approaching with the same polarity.

Inductive kick is a current effect. The switching of the ac to form dc current is not instantaneous. The change of current is not instantaneous at the zero crossing. The winding is an inductor. Therefore, there is a voltage drop that is dependent on the rate of change of the current.

$$V = L \frac{di}{dt}$$

### Neutral plane shift

Armature reaction is the effect of the distortion of the magnetic flux between the pole pieces as the load increases.

The neutral plane is the place where the velocity of the rotor wires exactly lines up with the magnetic flux lines. The result is induced voltage,  $e_{ind}$ , in the plane is zero. There is no back emf. The distortion of the flux lines causes a shift in the location where the rotor wire aligns with the magnetic field. This shift creates an opposing voltage.

The commutator brushes must short out the connection segments exactly when the voltage across the connections is zero. As the load increases, the flux distortion increases, causing the plane to shift. The brushes will arc since the location of the zero crossing point is not mechanically aligned with the brush location.

### Flux weakening

The second armature reaction problem is flux weakening. Most machines operate with the flux density very near saturation. At locations where the pole mmf adds to the armature mmf, a small increase in flux occurs. At other locations where the pole mmf subtracts from the rotor mmf, a larger decrease in flux occurs. The average is a decrease in flux.

Flux weakening has effect on the electrical voltage and the torque.

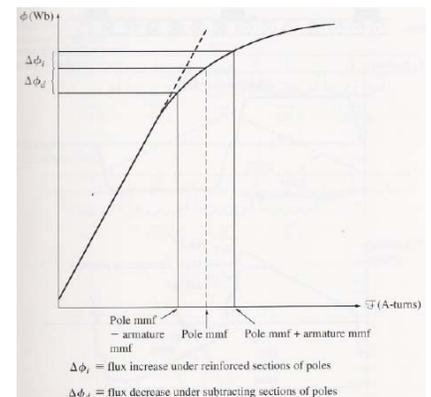
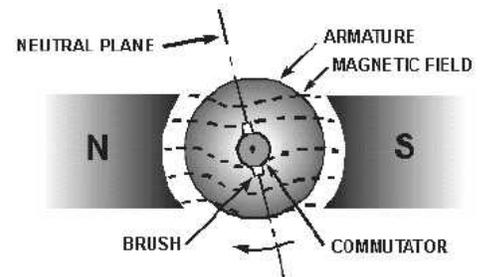
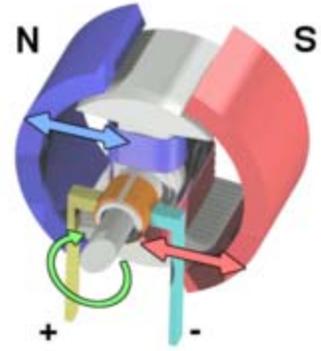
$$\tau_{ind} = K \phi I_A$$

$$E_A = K \phi \omega$$

### Compensation

Three techniques are used for compensation. Armature reaction neutral plane shift can be corrected by shifting the location of the brushes. However, this makes the field less effective and as a result adds to the weaker field.

Compensating windings and interpoles are two techniques that cancel armature reaction, which eliminates the need for shifting brushes. Commutating poles are interpoles are placed halfway between the pole pieces. This places them



above conductors being commutated. They are connected in series with the rotor windings. They do not change flux weakening, but do correct the brush arcing. They are very common in medium sized machines.

Compensating windings are cut into the face of the poles. This requires a large machine and the process is relatively expensive. Therefore only large, heavy duty machines tend to use the compensation. The great benefit is the correction of flux weakening which improves performance under load.

## 7.5 Model

DC Machines are the typical example of a Thevenin equivalent for the armature and a magnetizing inductance for the field. The field is a stationary stator and the armature is a rotating rotor.

The field can be connected separately, parallel, or in series. Other than changing the value of the voltage, the calculations are very similar. However, the performance is very different.

### Generic Relationships

The magnetic flux is determined by the field current.

$$\lambda = Li = \phi \mathcal{R}$$

$$\mathcal{F}_{mmf} = N_F I_F$$

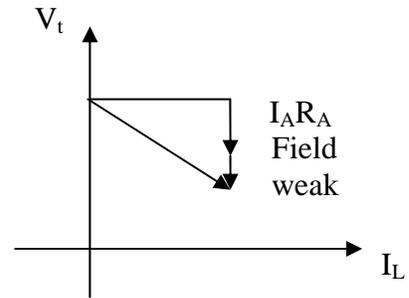
$$I_F = \frac{V_F}{R_F}$$

The flux couples to the armature to produce voltage and torque.

$$\tau_{ind} = K\phi I_A \Rightarrow I_A = \frac{\tau_{ind}}{K\phi}$$

$$E_A = K\phi\omega = K_f i_F \omega$$

$$\frac{E_{A \text{ actual}}}{E_{A \text{ reference}}} = \frac{n_{\text{actual}}}{n_{\text{reference}}}$$



### Separately Excited

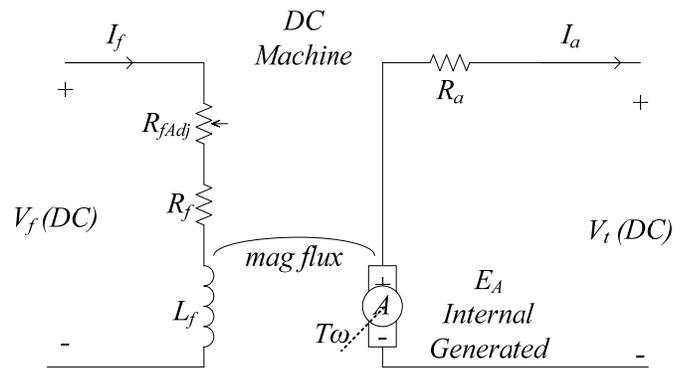
A separately excited machine has different dc voltage on the field and the armature. Permanent magnetic machines have a fixed field, so they are simple to operate.

$$V_t = E_A - I_A R_A$$

$$I_L = I_A$$

$$I_F = \frac{V_F}{(R_F + R_{adj})}$$

$$V_F = I_F (R_F + R_{Fadj}) \text{ V}$$



### Shunt Connected

A shunt excited machines has the field connected across the terminals. The advantage is only one power supply is required.

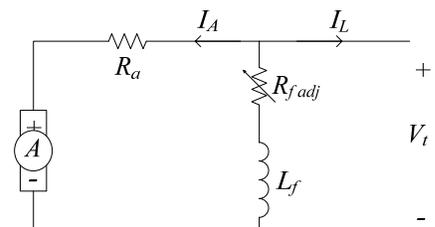
$$I_A = I_F + I_L$$

$$V_F = V_T$$

The terminal voltage controls flux, torque, and speed.

$$V_T = E_A + I_A R_A$$

$$V_T = K_f i_F \omega + I_A R_A$$

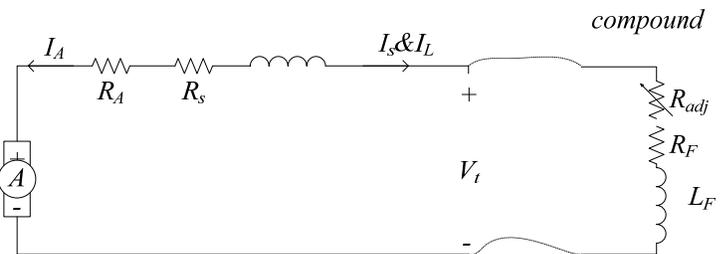


$$V_T = K\phi\omega + \frac{\tau_{ind}}{K\phi} R_A$$

$$\omega = \frac{V_T}{K\phi} + \frac{R_A}{(K\phi)^2} \tau_{ind}$$

## Series Connected

A series connected machine shares the current in the field and armature. This results in an increase in current to the field as the load increases. Speed regulation is poor, but a large quantity of power is available. These are used for vehicle starters, conveyors, and trolleys. Generators are used as welders.



$$V_t = E_A + I_A(R_A + R_S)$$

$$I_A = I_S = I_L$$

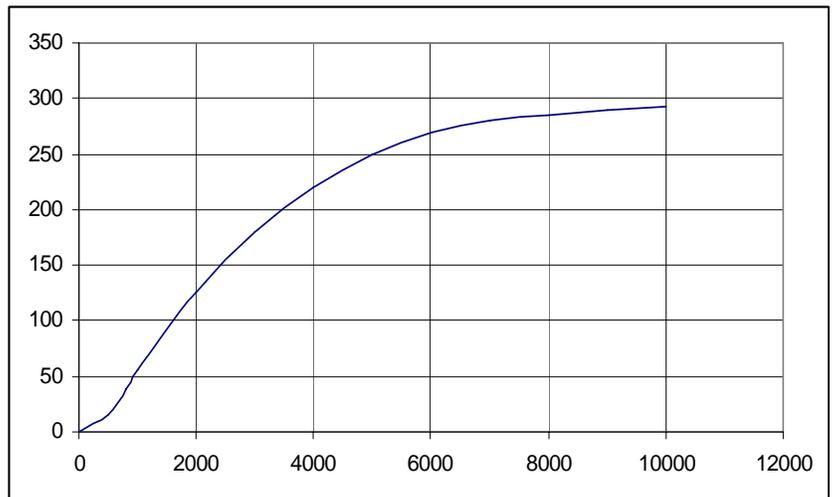
## 7.6 Magnetization curve

The magnetization curve is mmf (A-turns) on the horizontal and flux (Weber) on the vertical. For a dc machine the curve becomes a plot of the field current on the horizontal versus the internal generated voltage on the vertical.

$$E_A = K\phi\omega = K_1 i_F \omega$$

$$I_F = \frac{V_F}{(R_F + R_{adj})}$$

The internal generated voltage depends on the flux and the speed of the machine. The magnetization curve for the machine is based on a rated speed,  $n_0$ . If the machine is operated at a different speed, then the proportional voltage is calculated from the speed ratios.

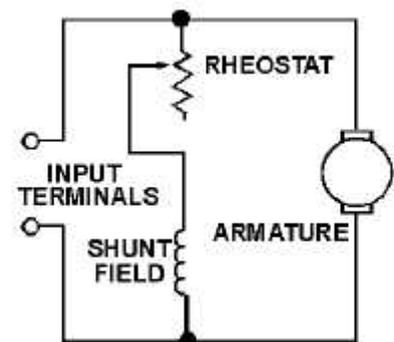


$$\frac{E_{A \text{ actual}}}{E_{A \text{ reference}}} = \frac{n_{\text{actual}}}{n_{\text{reference}}}$$

## Speed control

If the voltage is changed, then the speed will change. This characteristic permits a dc machine to be used as a variable speed motor. The speed is changed by changing the current in the field or by changing the current in the armature.

Speed is usually controlled by a rheostat connected in series with the field windings. When the resistance of the rheostat is increased, the current through the field winding is decreased. When the field current is decreased, the field flux is reduced, and the counter emf decreases. This permits more armature current. Therefore, the motor speeds up. When the field current is increased, the field flux is increased. More counter emf is developed, which



opposes the armature current. The armature current then decreases and the motor slows down.

When the voltage applied to the armature is decreased, the armature current is decreased, and the motor again slows down. When the armature voltage and current are both increased, the motor speeds up.

In a series motor, the rheostat speed control may be connected either in parallel or in series with the armature windings. In either case, moving the rheostat in a direction that lowers the voltage across the armature lowers the current through the armature and slows the motor. Moving the rheostat in a direction that increases the voltage and current through the armature increases motor speed.

### Direction of rotation

The direction of rotation of a dc motor depends on the direction of the magnetic field and the direction of current flow in the armature. If either the direction of the field or the direction of current flow through the armature is reversed, the rotation of the motor will reverse. Generally, the field excitation voltage is reversed. Ordinarily, a motor is set up to do a particular job that requires a fixed direction of rotation. For most machines, a fixed direction is all that is required. However, some machines that drive vehicles require operation in both directions. Gun turret and missile launcher control are two examples.

### **7.7 Dc motor project**

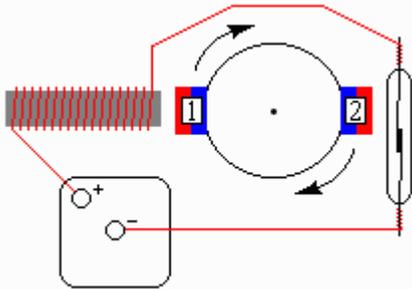
A brushless dc motor is the simplest rotating machine to construct as a project. It simply consists of a permanent magnet field, a coil that can rotate, and a switch to provide commutation. Although there are numerous project motor designs, this approach to switching the armature is provides the most consistent results.

Parts list	
Rod	Battery Holder
Magnet Wire	Axle
Base board	Four Mounts
Power Switch	Four Magnets
Reed Switch	

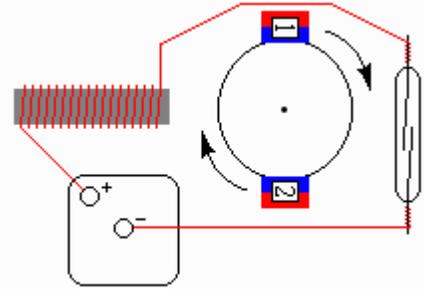
Place magnets on opposite sides of the axle. Verify the polarity of the magnets. Mount the axle so that it can spin freely. Construct an electromagnet on a ferromagnetic rod. Mount the electromagnet so that one end is very near the magnets when the axle spins. Mount the reed switch opposite the electromagnet so that it will make and break contacts as the axle spins the magnets. Connect the battery, electromagnet, and reed switch in series. An optional power switch may be inserted in the circuit.

When magnet # 2 gets close to the reed switch the two contacts inside the glass tube get magnetized and touch each other. This causes the electromagnet to push magnet #1 away.

When the magnets spin away, the reed switch demagnetizes and gets disconnected. This creates an open circuit disabling the electromagnet. The magnets continue to spin due to inertia until magnet #1 gets in working range of the reed switch.



The reed becomes magnetized again and its contacts connect together making the electromagnet push magnet #2 away. This process continues until the power source is disconnected or depleted, or the reed switch is moved out of working ranges.



### **5.9 Example**

A, 50 hp, 250V, 100 RPM, DC shunt motor without compensating windings has an armature resistance (including the brushes and interpoles) of 0.06 n. Its field circuit has a total resistance  $RF + Radj$  of 50 n, which produces a no-load speed of 1200 r/min. There are 1200 turns per pole on the shunt field winding, and the armature reaction produces a demagnetizing magnetomotive force of 840 A-turns at a load current of 200 A. The magnetization curve of this machine is shown in the Figure.

- a. Find the speed of this motor when its input current is 200 A.
- b. Repeat the process for 100 A.

c. Calculate and plot the torque-speed characteristic for this motor.

**Solution**

If  $I_L = 200$  A, then the armature current of the motor is

$$I_A = I_L - I_F = I_L - \frac{V_T}{R_F}$$

$$= 200 \text{ A} - \frac{250 \text{ V}}{50 \Omega} = 195 \text{ A}$$

The figure is the magnetization curve of a typical 250-V DC motor, taken at a speed of 1200 r/min.

The internal generated voltage of the machine is

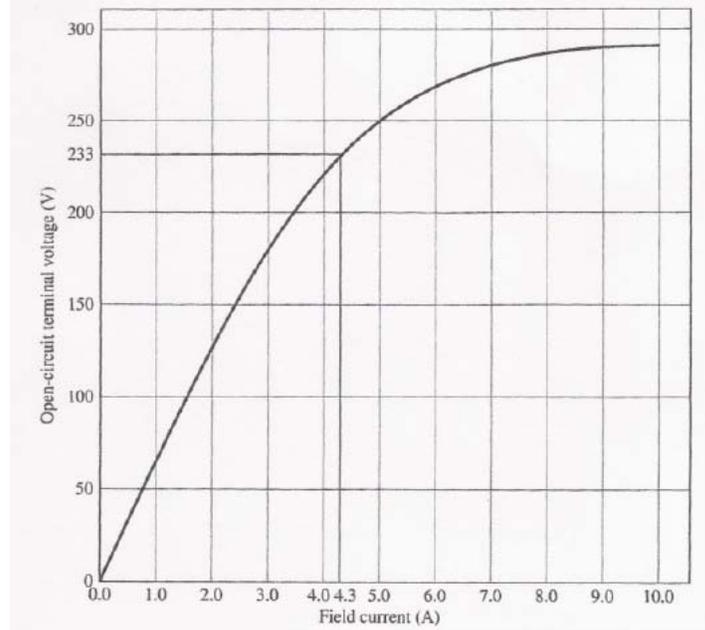
$$E_A = V_T - I_A R_A$$

$$= 250 \text{ V} - (195 \text{ A})(0.06 \Omega) = 238.3 \text{ V}$$

At  $I_t = 200$  A, the demagnetizing magnetomotive force due to armature reaction is 840 A-turns, so the effective shunt field current of the motor is

$$I_F^* = I_F - \frac{\mathcal{F}_{AR}}{N_F}$$

$$= 5.0 \text{ A} - \frac{840 \text{ A-turns}}{1200 \text{ turns}} = 4.3 \text{ A}$$



From the magnetization curve, this effective field current would produce an internal generated voltage  $E_{A0}$  of 233 V and speed  $n_o$  of 1200 r/min. The internal generated voltage  $E_{A0}$  would be 233 V at a speed of 1200 r/min. Since the actual internal generated voltage  $E_A$  is 238.3 V, the actual operating speed of the motor must be

$$\frac{E_{A \text{ actual}}}{E_{A \text{ reference}}} = \frac{n_{\text{actual}}}{n_{\text{reference}}}$$

$$n = n_{\text{reference}} \frac{E_{A \text{ actual}}}{E_{A \text{ reference}}} = 1200 * \frac{238.3}{233} = 1227 \text{ rpm}$$

**5.10 Exemplars**

An exemplar is typical or representative of a system. These examples are representative of real world situations.

**5.11 Applications**

Applications are an opportunity to demonstrate familiarity, comfort, and comprehension of the topics.