Electron DC Motors and Generators

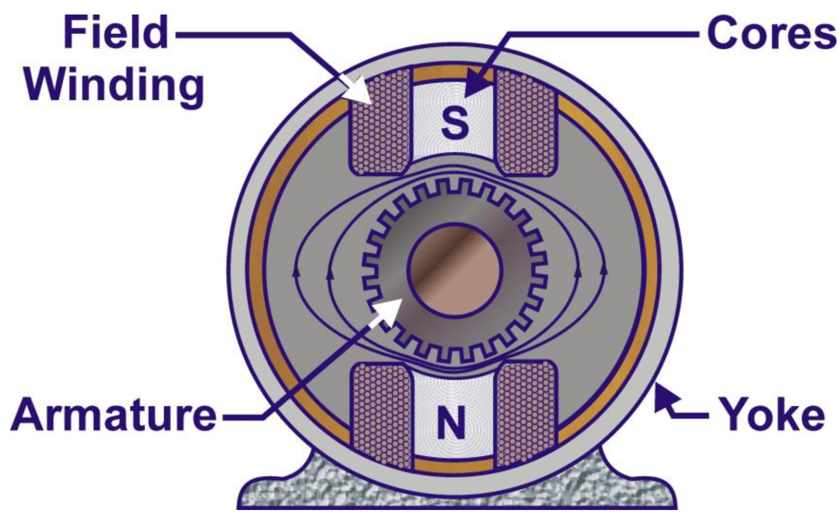
A. DC Motors and Generators

1. DC Generator Construction

    a. Dynamos convert mechanical energy to electrical energy or electrical energy to mechanical energy. A dynamo driven mechanically by a prime mover, such as a steam turbine or combustion engine, which delivers electrical energy to an electric light or a machine is called a generator. An electric dynamo whose mechanical rotation drives mechanical devices, such as pump shafts or machine tools, is a motor. DC generators are rated by wattage produced, without overheating, at a rated voltage and speed, whereas AC generators are rated in volt-amperes. Motors are rated by horsepower used, without overheating, at rated voltage and speed.

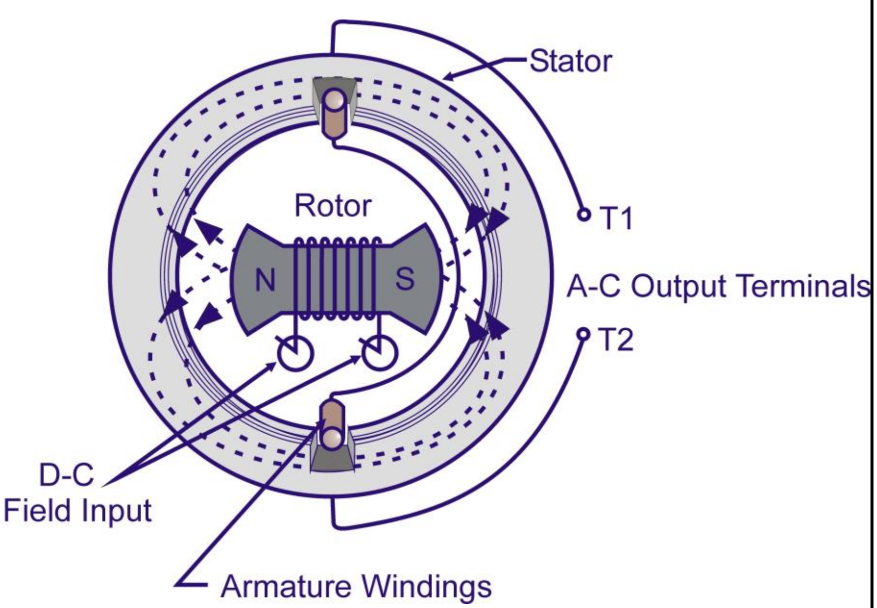
2. Types of Generators

    a. In DC and AC generators, relative motion between the conductor and magnetic field is set up by rotating either the armature or the field. Every generator has a rotor (rotating windings) and a stator (stationary windings). Either can be used to produce the magnetic field. The simple generator (Picture 1) uses the stator to set up magnetic north and south poles, shown as bar magnets, electro-motive force is induced in the rotating coil (rotor). The term armature is used to designate the load carrying portion of the machine; for a generator, it is the set of windings into which an emf is induced. Armatures can be stationary, as in the main generator, or rotating, as in Picture 1.



Picture 1, Simple Rotating Armature Generator

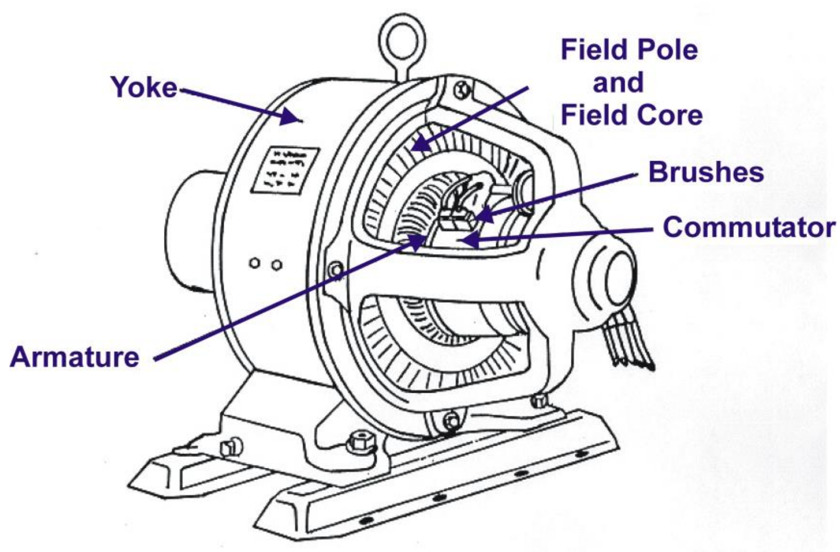
b. In some generators, a steady DC voltage is passed through windings of the rotor (Picture 2). As the rotor turns, rotor magnetic flux cuts stator windings and induces a voltage. These generators use the stator as the armature and are called rotating field generators. Most DC generators have rotating armatures; this chapter will concentrate on this type.



Picture 2, Simple Rotating Field Generator

3. Components

a. The DC generator field frame or yoke is a mechanical support for field pieces. It is usually made of annealed steel to reduce reluctance (recall, reluctance is resistance to magnetization) in the magnetic circuit. Attached to either side of the yoke are end bells which support rotor bearings and brush assemblies (Picture 3).



Picture 3, DC Generator

b. Magnetic flux is usually established by field windings, or coils, not permanent magnets. Field windings receive DC current from an external source and may be connected directly across the armature for self excitation. Concepts of excitation are discussed later. Field windings are wound around pole pieces for support and mounted on the inside circumference of the yoke (Picture 1). Pole faces are shaped to fit the curvature of the rotor. Pole pieces, always in pairs, are mounted across from each other and wound to provide a south pole on one side of the rotor and a north pole on the other. Magnetic flux is established between pole pieces and passes through the rotor. An assembly, of one or more pole sets is called a stator and is stationary.

c. The rotor is mounted on a shaft and rides on rotor bearings inside the end bells (Picture 1). The outer surface of the rotors cylindrical core is slotted to secure the rotor coils.

d. An electromotive force (emf) is induced in the rotor as it rotates through the magnetic field. Free ends of the rotor coil are connected to the commutator, forming a closed circuit. The commutator consists of a number of wedge-shaped segments, or bars, of copper, assembled into a cylinder. There is one pair of copper segments for every loop contained in the rotor. Generator brushes ride on the commutator surface and make a sliding contact point. They carry current from the commutator to the external circuit. Brushes, usually made of a mixture of carbon and graphite, are held in position by brush holders. Springs maintain proper pressure against the commutator.

e. Most generator rotors have many individual loops, therefore their commutators have many copper segments. Commutator segments are insulated from each other and mounted on the rotor shaft . A generator with only a single loop (Picture 4) will have one set of copper segments in the commutator.

f. As the rotor rotates on its shaft, it cuts lines of flux set up by the field poles in the stator. This produces emf in each rotor coil. This emf is proportional to the magnetic flux cut per unit time. Ends of each rotor loop are connected to a segment of copper in the commutator. Voltage on any single copper piece in the commutator varies in magnitude and polarity (AC) as its coil rotates. The commutator is mounted on the rotor and rotates with it. Brushes are stationary and mounted so the commutator segment currently touching is at the same position in the magnetic field as the previous segment. This occurs because each loop passes the magnetic pole while the brush touches the commutator. Therefore, voltage conducted by the brush is DC. This DC is transmitted to the generator terminals and becomes available to an external load circuit.

B. Operation of a Simple DC Generator

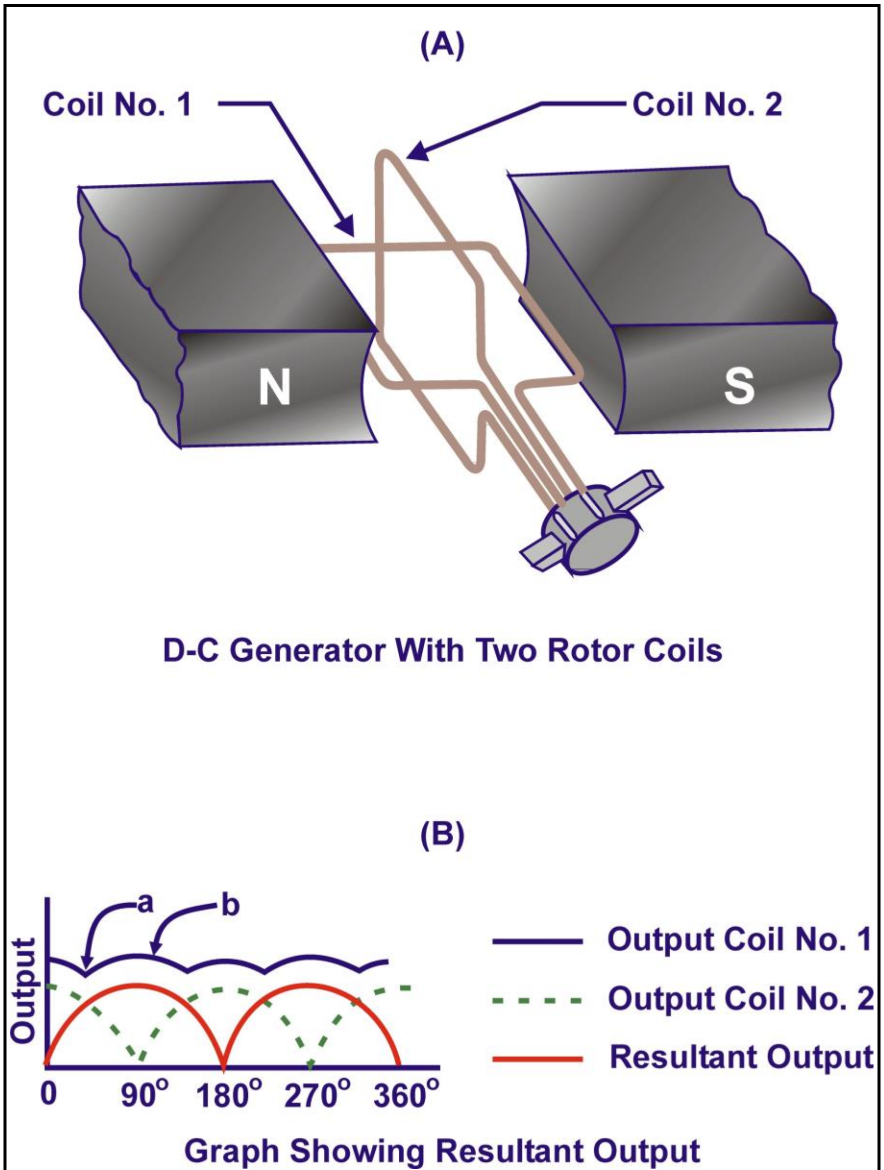
1. Simple Generator

   a. A generator is a machine which employs electromagnetic induction to convert mechanical energy into electrical energy. Voltage is induced by electromagnetic induction when a conductor is cut by

   b. a magnetic field. A generator consists of a number of conductors and a magnetic field, from

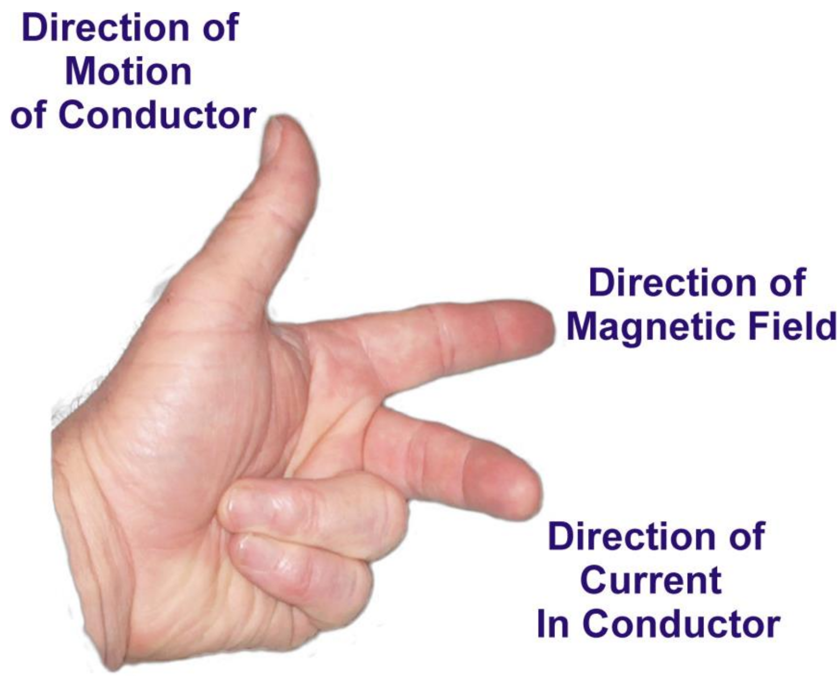
   c. permanent magnets or electromagnets, arranged so that a relative motion between the two induces a voltage in the conductors.

   d. A simple generator consists of a single coil of wire rotating between poles of a magnet. An emf is induced in the wire as it rotates through the magnetic field. Picture 4 shows a simple generator where a coil is rotating counterclockwise in a magnetic field. At time 1, coil A is moving upward and coil B down. After 90E of rotation, at time 2, the conductors are moving parallel to the magnetic field, no induced voltage. At 180E of rotation, time 3, conductors are perpendicular to magnetic flux and induced voltage is maximum again. The direction of current in each coil has changed direction from time 1, but due to the commutator rotation, current direction in the load will be the same as at time 1.



Picture 4, Simple DC Generator Operation

e. A method to determine the direction of current in a conductor is the left-hand rule for generators. This rule (Picture 5) is stated as follows: with thumb, forefinger, and middle finger of the left hand perpendicular to each other, point the thumb in the direction of motion, the forefinger in the direction of the magnetic field, , and the middle finger will point in the direction of induced current.



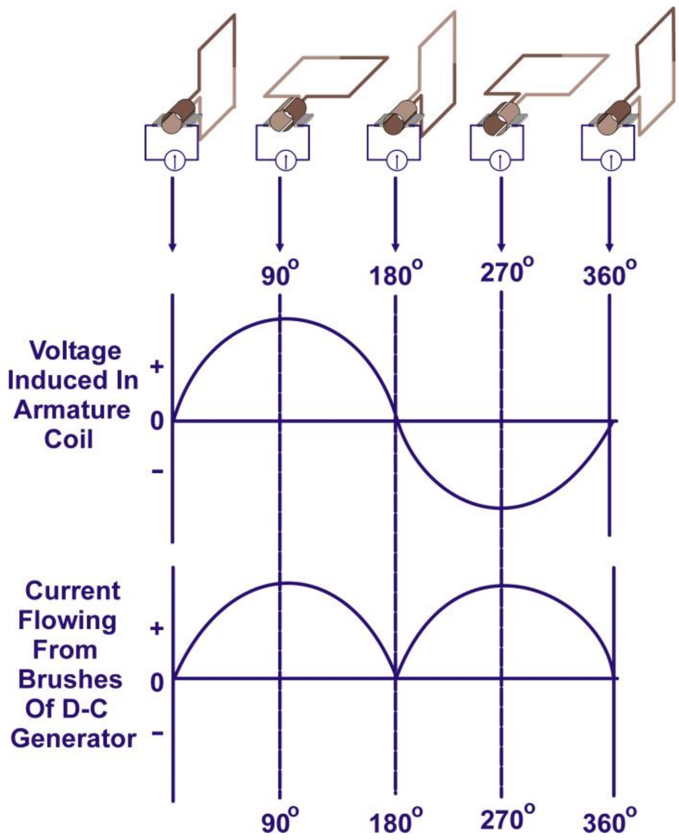
Picture 5, Left Hand Rule for Generators

f. To apply the left-hand generator rule, it is always necessary to assume the magnetic field is stationary and the conductor is moving through the field. If the generator happens to have a rotating field mentally stop the field and rotate the armature in the proper relative direction.

g. In Picture 4, the loop containing sides A and B represents a rotor with only one coil wrapped around it. Since this generator has only one loop, the commutator consists of only one set of copper segments (E and F). The generator is also a two pole generator (two pole pieces) represented by the north and south bar magnets. The rotor is being turned by some prime mover, such as a turbine, around the axis.

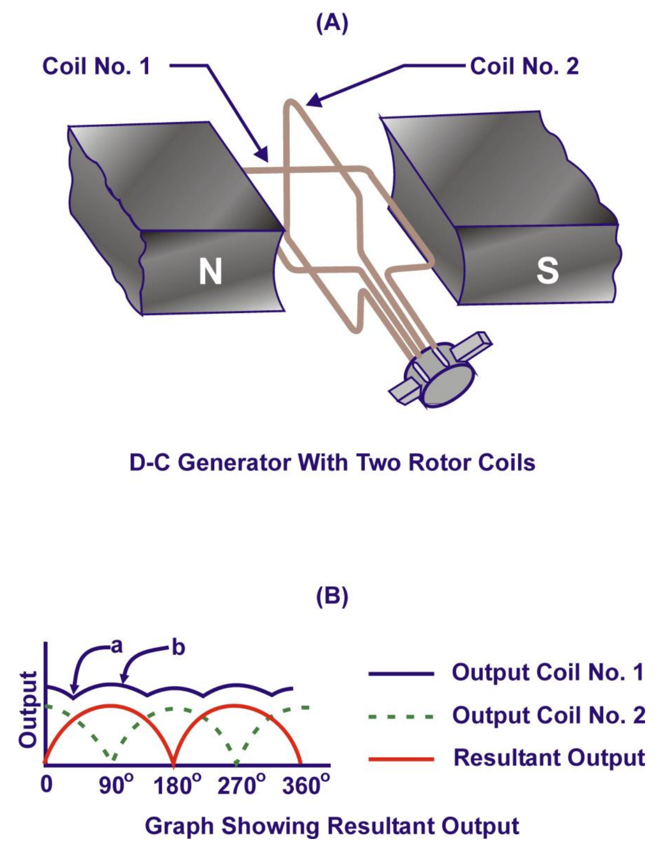
2. Ripple

a. Although current through the load in Picture 4 is always in the same direction, it is not a steady DC current. Voltage generated in the armature coil and applied to the brushes, and therefore the load, varies from zero to maximum, and back to zero twice each revolution. Variations in brush voltage are shown in Picture 6, which is a graph of pulsating DC voltage for one revolution of a single-loop. This characteristic of pulsating voltage is called ripple and is unsuitable for most applications.



Picture 6, Ripple of a Single-Coil DC Generator

b. In practical DC generators, more coils and commutator segments are used to produce an output voltage waveform with fewer ripples. Picture 7 shows the reduction of ripple in DC voltage when two coils are used instead of one. Since there are now four commutator segments in the commutator and only two brushes, voltage cannot fall any lower than point A. Therefore, ripple is limited to voltage rise and fall between points A and B. By adding more rotor coils, ripple can be further reduced until it is negligible and generator output is essentially steady DC.



Picture 7, Two-Coil Generator Waveform

C. Armature Losses

1. There are three losses in every armature, whether an AC or DC armature in a generator or a rotor or stator. These are I^2R (or copper) losses in the windings, eddy current loss in the core, and hysteresis loss due to realignment of domains in the core.

2. Power lost (in the form of heat) from electrical resistance to current flow in the windings is called I^2R loss. This loss varies directly with armature

resistance and the square of armature current. Previously, we learned that DC power is equal to the product of the square of current and resistance

3. (I^2R). Since armature windings present some given resistance, power is lost in the form of heat. This is a major source of heat in a generator.

4. Total armature resistance is a given value, plus or minus small changes due to winding temperature variations, and part of generator design. But armature current varies as generator load varies. Therefore, as current increases due to a load increase, power dissipated in the form of heat will increase as a square function.

   a. Example 1: Compare the I^2R losses, when armature current is increased from 1800 amps to 3600 amps, for a DC generator with an armature resistance of 0.05 ohms

   b. Answer:

      1) Calculate the I^2R losses for the initial load conditions.

      $P = I^2R = (1800)^2 \times 0.05 = 162$ Kw

         a) Calculate the I^2R losses after the load increase.

         $P = I^2R = (3600)^2 \times 0.05 = 648$ Kw

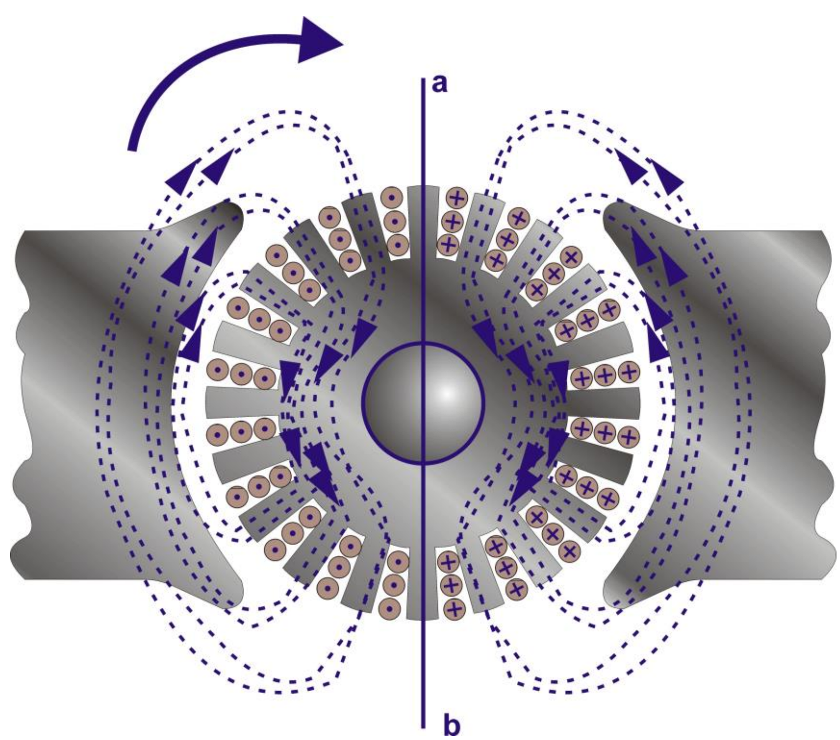
5. Armature current doubles but the power loss in the form of heat increases by a factor of four (2 squared is 4). Had the current tripled, I^2R losses would have increased by a factor of nine.

6. All generators experience I^2R losses in both the rotor and stator. Anything with a lot of wire has significant I^2R losses. Design features keep this loss to a minimum to limit heat in the generator and wasted power. This is accomplished by minimizing total armature resistance. Temperature rise

inside the generator can be limited by the use of one or more of the following: ventilating ducts, forced ventilation, and circulating liquid coolant.

7. Eddy Current

   a. If a DC generator armature core is made of solid iron (Picture 8) and exposed to a rapidly changing magnetic field, a voltage is generated in the armature core. Thus, induced currents alternate through the core, first in one direction and then in the other. These induced currents are called eddy currents.



Picture 8, Eddy Currents in DC Generator Armatures

   b. Eddy currents are kept to a low value by sectionalizing or laminating the armature core. For example, if the core is split into two equal parts and these parts are insulated from each other, induced voltage in each section of iron is halved and because resistance varies inversely with the cross sectional area, the resistance of each eddy current path is doubled. If a 10 volt potential is induced in the core and resistance of the path for eddy currents is 1 ohm, eddy current loss is E^2) R, or $(10)^2$) 1 = 100 watts. Voltage induced in each section is 10) 2, or 5 volts. Area is halved and the resistance of each eddy current path is 2 ohms. Loss in each section is E^2) R, or $(5)^2$) 2 = 12.5 watts, and total armature loss is 12.5 watts x 2 sections, or 25 watts. This value represents one-fourth the original power loss.

c. Reducing thickness of the core to one-half its original value reduces the loss to one-fourth the original loss. Thus, eddy current losses vary with the square of the thickness of a core section. If the armature core is sufficiently subdivided into multiple thin sections, or laminations, eddy current loss is reduced to a negligible value. Reducing the thickness of laminations reduces the magnitude of induced emf in each section and increases resistance of the eddy current paths. Laminations in a small generator are typically 1/64 inch thick. They are insulated from each other by a thin coat of lacquer or, in some instances, simply by oxidation of surfaces due to contact with the air while laminations are being processed. Insulation need not be high because the induced voltage in each section is very small.

d. All electrical rotating machines (generators and motors) are laminated to reduce eddy current losses.

8. Hysteresis Loss

a. When an armature is exposed to a changing magnetic field, the magnetic domains of the armature change to hold alignment with the field. The amount of domain alignment varies depending upon field strength. These domains rotate with respect to domains not held in alignment. The rotation of the domains in the mass of iron produces friction against non-rotating domains and results in heat generation. Heat produced in this manner is identified as magnetic hysteresis loss. Heat treated, high strength, silicon steel with a low hysteresis loss is used in most DC generator armatures. Certain metals allow domains to rotate more freely than other metals. For example, soft iron has less hysteresis loss than steel. Soft iron is used for the core in transformers. Yet soft iron is not strong enough for armatures. After steel has been formed to the proper shape, laminations are heated to a dull red heat and allowed to cool. This process, called annealing, provides a metallic lattice structure (arrangement of atoms) which allows the domain to rotate more freely. Therefore, hysteresis losses are reduced.

D. Generator Excitation

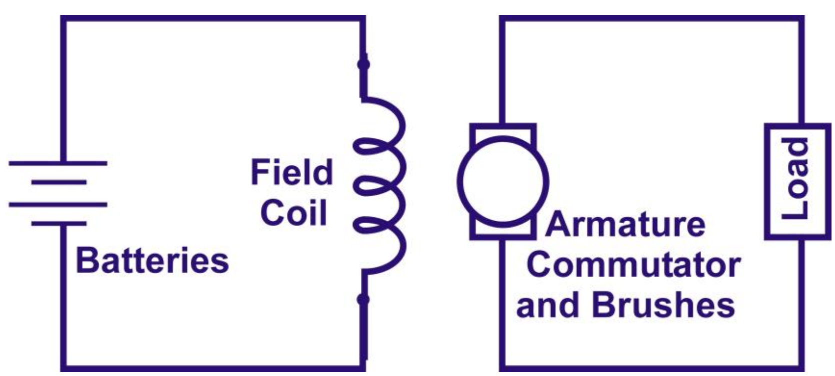
1. Need for Excitation

   a. The magnetic field of a generator can be produced by either permanent or electromagnets. Permanent magnets produce a magnetic field without any external energy involved. For this reason, most permanent magnet generators are used in hand held applications. Since large permanent magnets are both costly and not as strong as electromagnets, most generators use electromagnets for their magnetic field. The current can come either from the generator itself (self-excitation) or from some external DC source (external excitation). Without an excitation system, no magnetic field would exist.

2. The excitation field must be of constant strength and polarity during steady state conditions. Current used to produce an electromagnetic excitation field must be DC. If a constantly changing AC voltage was used, generator output voltage would change.

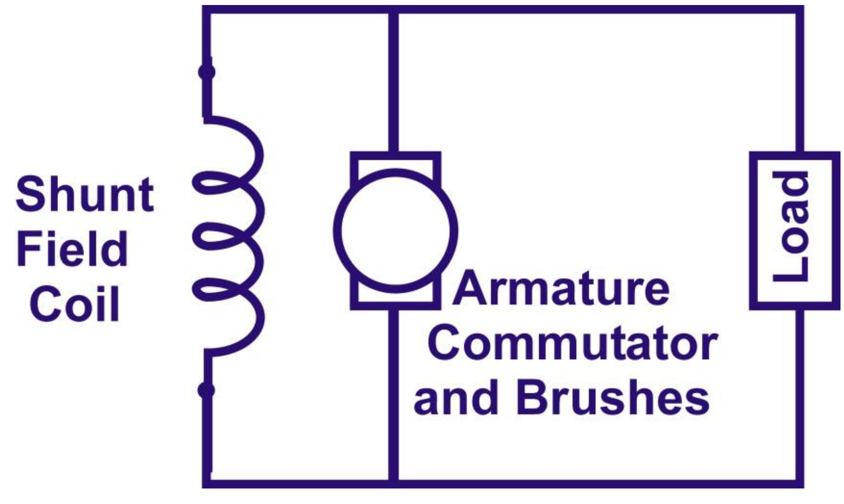
3. DC generators are classified by the way field windings are connected to the armature circuit. Direct current used to excite field coils of any generator may be obtained from storage batteries, a separate DC generator, or its own output. It is a common practice to keep this excitation current between 5 and 10 percent of the generator's rated current.

4. Since armature windings of any generator are in series with external load, an increase in the load current means an increase in current flowing through the armature windings. Because I^2R losses increase, generator output voltage decreases. If the generator's magnetic field is dependent upon output as in some generators discussed later, variations in armature voltage affect the field. In the externally excited generator, strength of the field does not depend upon load and, generator voltage is more constant (Picture 9). This separately excited generator is not in wide use today. However, such a generator is used where constant voltage is essential.



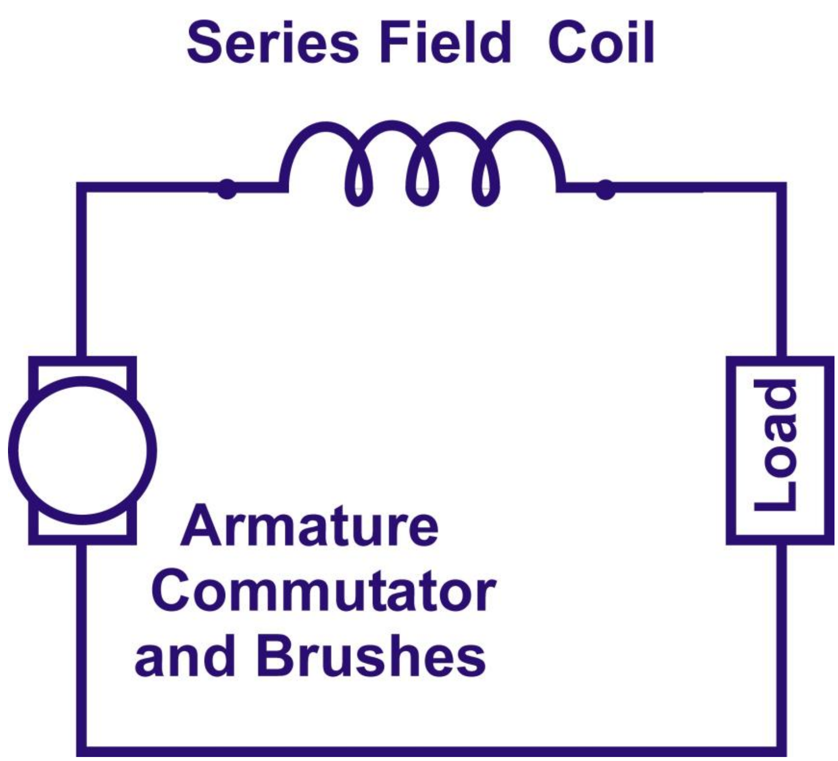
Picture 9, Separately Excited DC Generator

5. Another type of excitation used for generators is self-excitation. In this process, the generator supplies its own magnetic field. This is accomplished by taking a portion of the generator output and putting it through main field windings.
6. The generator does not generate any current until the armature starts rotating and cutting magnetic lines of force. Because field coils do not receive any current until the generator delivers it, residual magnetism of the field poles are required for startup. Field poles are made of iron and become magnetized as current flows through their field coils.
7. When the generator stops rotating and this current ceases to flow, field poles lose most of their magnetism. A certain small amount (residual magnetism) remains. When the armature starts rotating again, cutting of weak magnetic flux produces a weak induced current. All of this is fed back to field coils, increasing the strength of the magnetic field. The process continues to build up until the field reaches its normal strength. It takes about 20 to 30 seconds. If the generator has been standing idle for a long time, or the residual magnetism of the generator is small, or the time required to build up the main field is too long, it is necessary to use batteries to furnish the starting field current. As the generator starts delivering current, the batteries are removed. This is called flashing the generator. Many generators have an automatic circuit for flashing the field.
8. There are three basic types of self-excited generators. The shunt field generator is one in which the field coil is connected in parallel (or in shunt) with the armature windings and load (Picture 10).



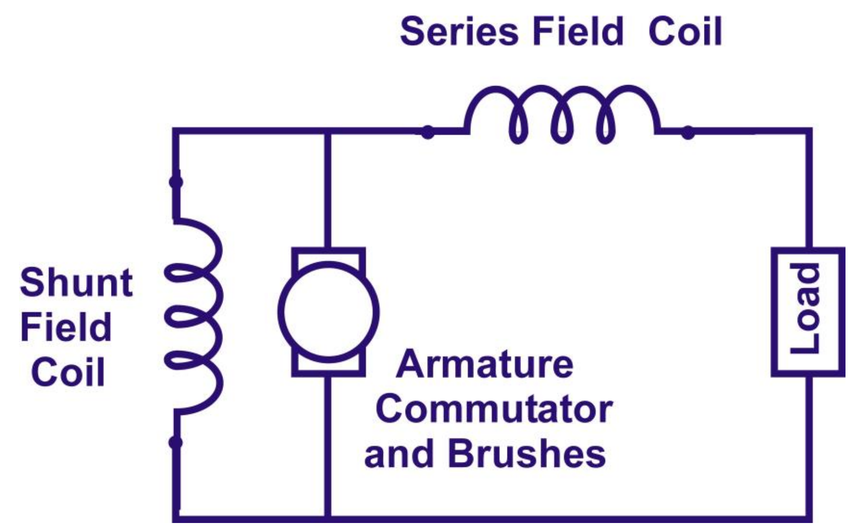
Picture 10, Shunt Field Generator

9. The series field generator is one in which the field coil is connected in series with the armature windings and load (Picture 11).



Picture 11, Series Field Generator

10. A compound field generator is one in which the characteristics of shunt and series fields have been combined (Picture 12).



Picture 12, Compound Generator

11. Voltage Regulation

    a. Amount of voltage produced by a generator depends upon three things: rotor speed, number of coils in the armature, and strength of magnetic field.

    b. It is not possible to change the armature winding after it has been installed in the generator. It is usually not feasible nor desirable to change the speed of the rotor. Therefore, the most practical method of controlling output voltage is by controlling strength of the magnetic field. The purpose of a regulation system is to control the magnetic field and, therefore, generator output voltage. This regulation is necessary since characteristics of a generator cause terminal voltage to drop as load increases. This is due to increased I^2R losses (more internal voltage drop). The regulation system increases the excitation field to offset increased I^2R losses and armature reaction.

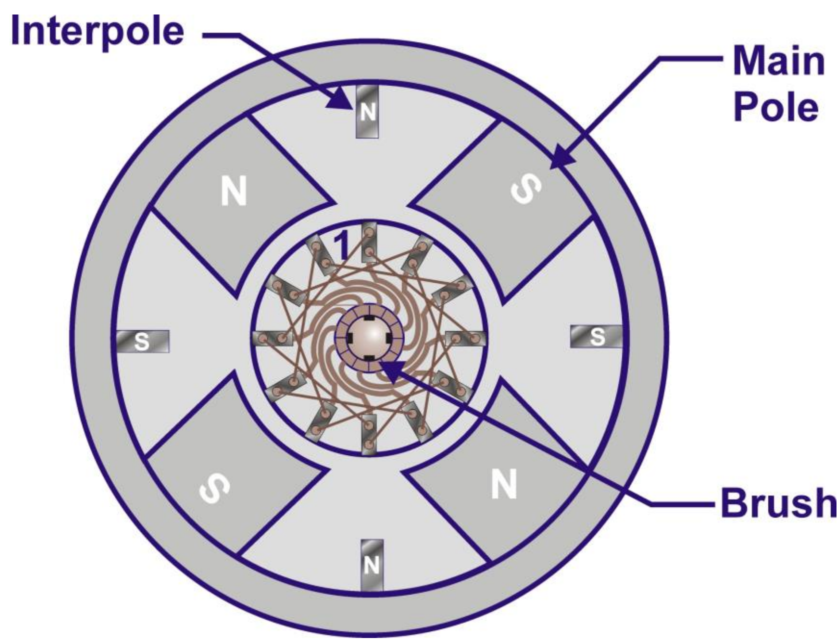
c. Most generators have a voltage regulation control system which operates in manual, automatic, or manual-automatic control. Voltage regulators often employ a variable resistor to change excitation field current. Controlling field current permits control of terminal voltage. Thus, the major difference between various voltage regulator systems is the method by which field current is controlled. When load changes are infrequent and small, manual control is sufficient to hold generator voltage at the desired value. When load changes are frequent and large, it is desirable to employ some form of automatic control. Concepts of field excitation and field regulation should not be confused. As described previously, field excitation is the process by which a magnetic field is produced in the generator and field regulation is the process used to control the strength of that field.

E. Direct Current Motors

1. Construction

a. Construction of a DC motor is essentially the same as that of a DC generator. A generator converts mechanical energy into electrical energy, whereas a motor converts electrical energy back into mechanical energy. When a suitable source of direct voltage is applied across the normal output terminals of a DC generator, the generator will motorize. When motorized, current in each armature coil is reversed with respect to its direction when operating as a generator. Polarity of the field poles does not change. When operated as a generator, the rotating commutator and associated carbon bushes serve as a rotary switch that switches the internal alternating current to direct current for the external circuit. If the same machine is operated as a motor, the commutator reverses action. Although direct current is supplied to the armature, switching action of the commutator and brushes reverses current in each armature coil each time the center of a coil passes the center of a main field pole. It is this reversal of armature current which causes mechanical force on a conductor to be in the same direction under a north pole as near a south pole.

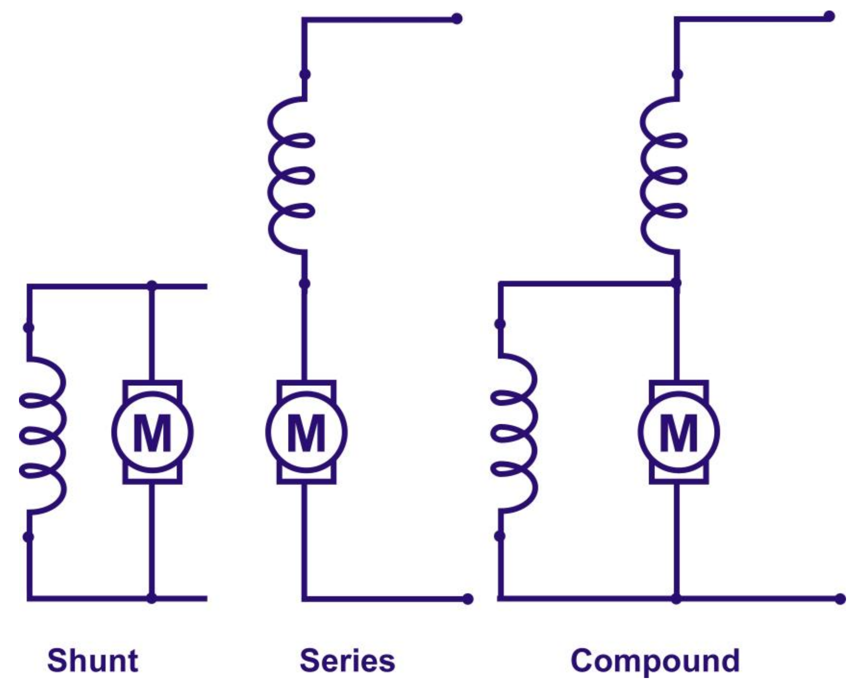
b. Practical DC motors depend upon interaction between field flux and one or more current-carrying conductors on its rotor. Conductors are wound in slots in the rotor (Picture 13). The rotor is mounted on bearings and is free to rotate in the magnetic field. The rotor has many slots into which many turns of wire are inserted. This increases the number of rotor conductors and produces a greater, more evenly distributed force upon the rotor. Force is also increased by increasing poles in the field.



Picture 13, Practical DC Motor

c. Shunt motors have field coils connected in parallel with the armature circuit. This type of motor, with a constant applied voltage, develops variable torque at an essentially constant speed, even under changing load conditions. A series motors has field coils connected in series with the armature circuit. This type of motor develops variable torque but its speed varies widely under changing load conditions. That is, speed is low under heavy loads, but can become excessively high under light loads, called runaway. Motors with only a series field winding have extremely high starting torques. However, they must be directly coupled to the load to prevent loss of load and excessive speed.

d. Series motors are commonly used to drive electric cranes, hoists, and certain types of vehicles (such as electric trucks). Series DC motors are used extensively to start internal combustion engines (starter on a car). Compound motors have one set of field coils in parallel with the armature circuit and another set of field coils in series with the armature circuit. This type of motor is a compromise between shunt and series motors. It develops increased staring torque over the shunt motor and has less variation in speed than the series motor. Shunt, series, and compound motors are all DC motors designed to operate from constant-potential, variable-current DC sources. Diagrams of the basic types of DC motors are shown in Picture 14.

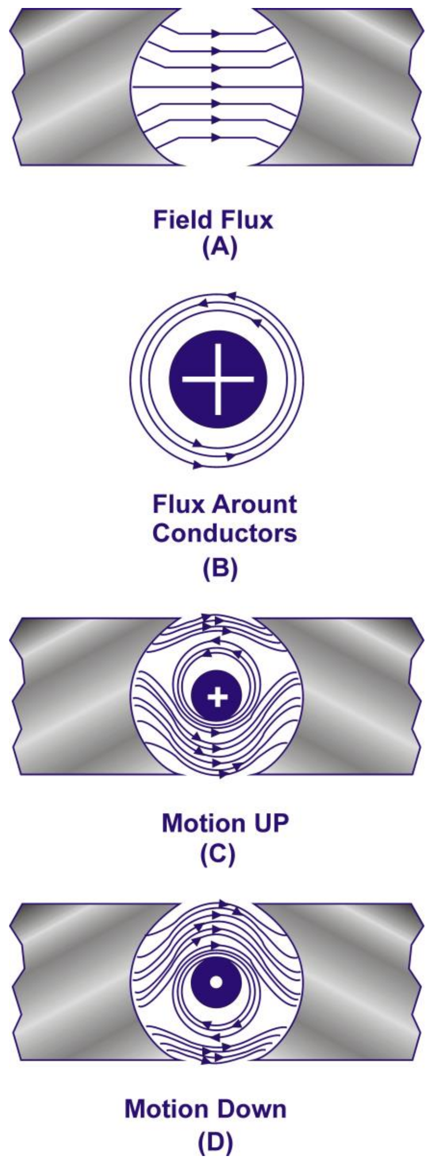


Picture 14, Schematic Diagrams of Basic DC Motor Types

2. Principle of Operation of DC Motors

   a. A DC motor operates because a current-carrying conductor placed in a magnetic field tends to move at right angles to the direction of the field (Picture 15).

   b. When a current-carrying conductor is placed in a magnetic field a force results in the direction of the vector cross product between the magnetic field and the current. The force causes rotor rotation, or conversion of electrical energy to mechanical energy.



Picture 15, Force Acting on a Current-Carrying Conductor in a Magnetic Field

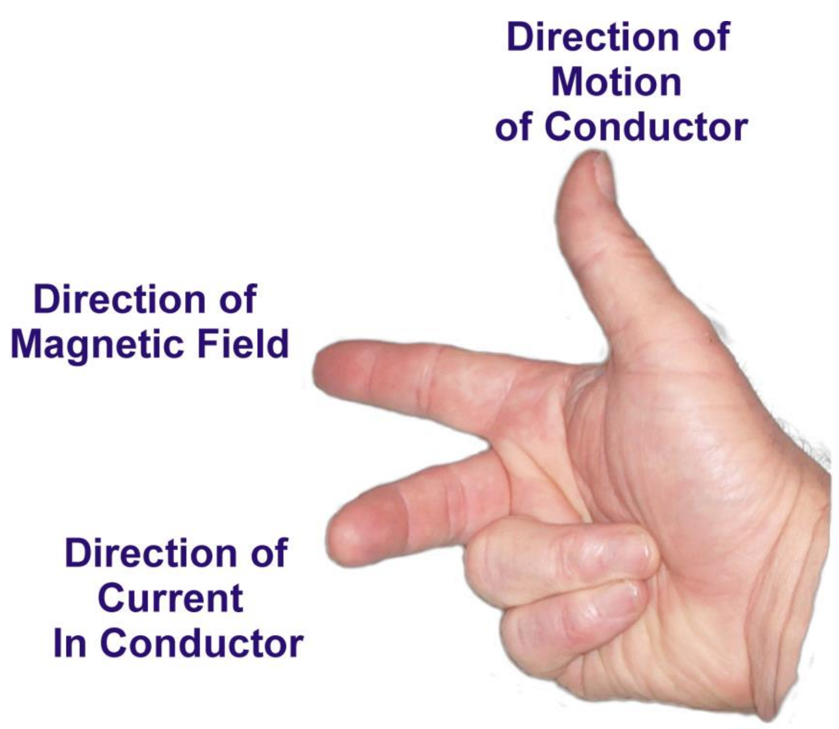
c. The amount of the force depends on the magnetic field strength and armature (conductor) current.

d. The motion of the conductor (rotor rotation) establishes the conditions for a voltage to be induced in the conductor. Applying vector cross products for this determines the direction of the induced voltage. In all cases, the induced voltage will oppose the current to the motor. This induced voltage, (counter emf or generator action in a motor) will limit the armature current.

e. To reverse direction of a DC motor it is necessary to reverse polarity of the magnetic fields or direction of current, but not both. If both were reversed, the direction of rotation would be the same.

3. Right-Hand Rule for Motors

a. A method for determining the direction of motion of a current-carrying conductor in a magnetic field is the Right-Hand Rule for Motors (Picture 16).



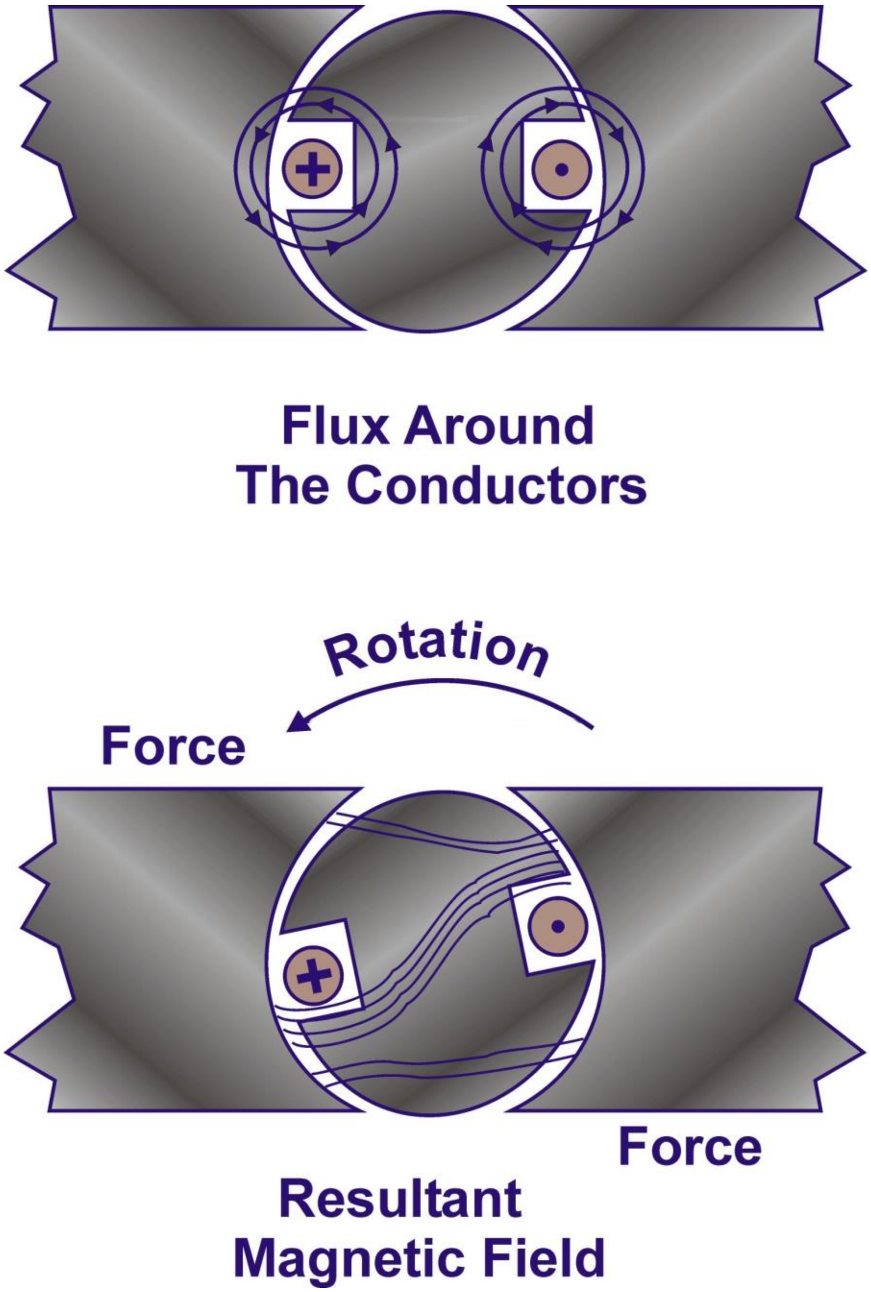
Picture 16, Right-Hand Rule for Motors

b. Recall that the left-hand rule applies to generators. Because a motor is the opposite of a generator, the right hand is used to determine direction of conductor motion. The rule is stated as follows: with thumb, forefinger, and middle finger of the right hand set perpendicular to each other, point the forefinger in the direction of the magnetic field (flux) and the middle finger in the direction of the current in the conductor. The thumb points in the direction of resultant conductor motion. The fingers represent the same parameters as they did in the left-hand rule for generators. This time, they determine direction of motion rather than direction of induced current. Also, by changing polarity (reversing the field direction) of field voltage or direction of conductor current, the direction of rotation of the motor is reversed.

4. Torque

   a. The force acting upon a current-carrying conductor in a magnetic field is directly proportional to field strength, the active length of the conductor (that part of the conductor contained in the rotor slot and lying under a pole face), and the value of current flowing through it. That force (or twist) on the rotor is torque and is measured in foot-pounds of force.

   b. In a motor, the length of the conductor is a fixed quantity. Therefore, the only variables are armature current and field flux. If field flux is constant, force acting on the conductor varies directly with rotor current. In other works, torque is proportional to applied armature current. If the conductor is wound around a rotor and rotor current flows in the direction shown in Picture 17A, there is an upward force on the left of the rotor and a downward force on the right of the rotor (Picture 17B). Net force, or torque, acting to turn the rotor is the sum of these two forces.



Picture 17, Two-Conductor Rotor

5. Horsepower

   a. Most motors are rated in horsepower (hp). Horsepower is a unit of power defined as the capacity of a mechanism to do work in a given unit of time. It is the equivalent of raising 33,000 pounds one foot in one minute, or 550 pounds one foot in one second. Since power is also measured in watts, watts and horsepower are interchangeable terms at a ratio of 746 watts to one horsepower. Horsepower of a motor can be determined if the following data is known: speed at which the rotor turns (in revolutions per minute or second), effective rotor radius at which the force acts, and total force acting at the tangent to this effective radius. Recall that work is accomplished only when a force acts through a distance. In other words, if force is applied to a building and it does not move, no work has been accomplished. Only if the building is moved, will work have been performed. When a force of one pound acts over a distance of one foot (one foot-pound of force), one foot-pound of work is accomplished. The rate at which this work is accomplished is power. If a shaft experiences 2000 foot-pounds of torque from the motor, but is stuck (not rotating), no power is being delivered by the motor to its load. Work occurs only of there is movement.

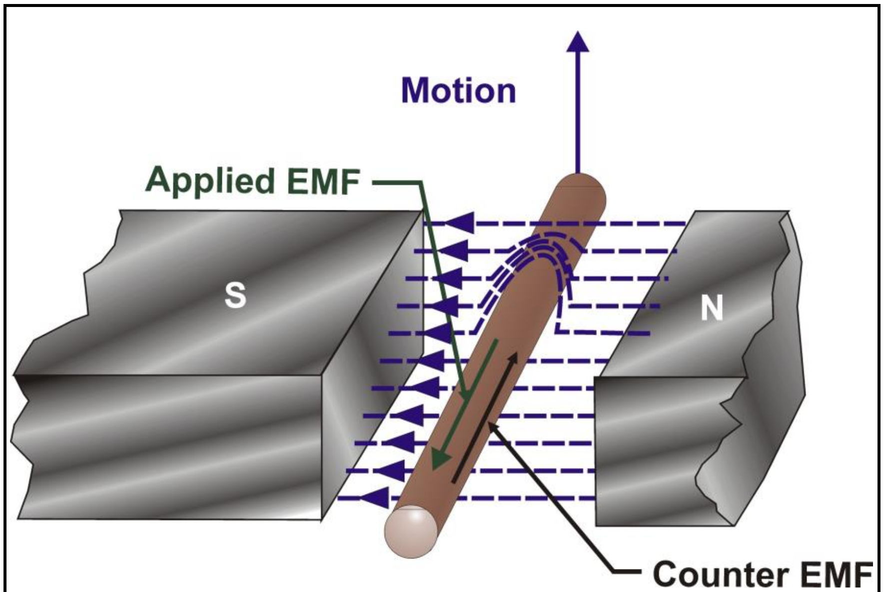
6. DC Motor Uses

   a. In nuclear power plants, DC motors are most commonly used on emergency pumps and high priority systems. Standby lubricating oil pumps for expensive turbines as well as containment isolation systems are commonly driven by DC motors.

F. Generator Action in a Motor

1. Generator Action

   a. The requirements to generate a voltage in the rotor of a motor exist: a magnetic field, conductors in the field, and relative motion between the two. As noted previously, this voltage is counter to the load current through the motor conductors (Picture 18).



Picture 18, Generator Action in a Motor

b. Counter voltage, or counter emf, is induced in the windings of any rotating motor armature and always opposes the applied voltage. This induced voltage is directly proportional to the speed of the armature and the strength of the magnetic fields. That is, counter emf is increased or decreased if speed is increased or decreased. The same is true if the field strength is increased or decreased.

c. An armature can be defined as a wire in which an electromotive force is produced. In a generator, the armature could be either the rotor (rotating armature generator) or stator (rotating field generator). But in a motor with voltage always supplied to the stator, the only induced electromotive force is counter electromotive force in the rotor. Therefore, for a motor, the rotor will always be the armature.

2. Effective Armature Voltage

a. Effective voltage in the armature (rotor) is equal to the applied voltage minus the counter emf. Current flowing through the armature varies directly with effective voltage and inversely with the armature resistance (R_a). This current can be calculated by:

$$I_a = \frac{E_a - E_c}{R_a}$$

Where:

I_a is the current flowing through the armature

E_a is the applied voltage across the armature

E_c is the counter emf

R_a is the armature resistance

3. Running Current

a. The current in a DC motor is directly proportional to the armature current is determined by the effective armature voltage (E_a – E_c) and the armature resistance (R_a). The value of armature current when the motor is at rated speed (i.e., when counter electromotive force of the armature is fully developed and stable) is called the running current. Meters which monitor motor current are measuring armature, or running, current.

G. Motor Starting

1. Starting Current

a. Because armature resistance of most motors is kept low, 0.05 to 0.5 ohms, to minimize I^2R losses, and counter emf does not exist until the armature begins to turn, the initial value of armature current will be quite high (Example 2). This is because full applied voltage will be across the armature and armature resistance determines current.

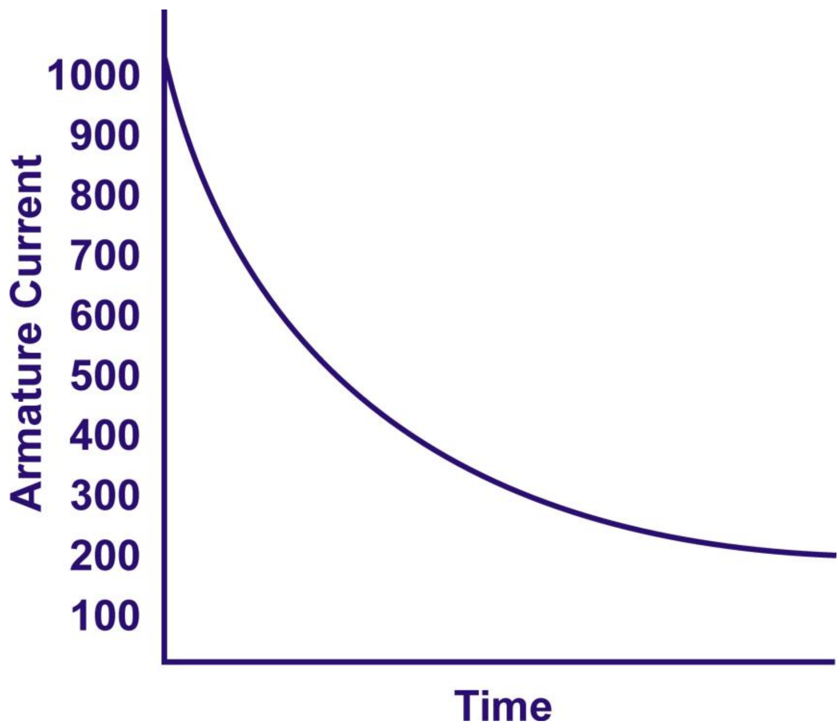
b. Example 2: 100 volts has just been applied to a motor with an armature resistance of 0.1 ohms. What is the armature current prior to the beginning of armature rotation?

c. Answer:

1) Solve for the armature current.

$$I_a = \frac{E_a - E_c}{R_a} = \frac{100 - 0}{.01} = 1000\,\text{amps}$$

d. As the armature accelerates towards its rated speed, the value of counter electromotive force builds up. This reduces the value of armature current (Picture 19). Motor current, which is proportional to the armature current from the time voltage is first applied until the motor is at rated speed, is called starting current. Its peak value can be 100 times the average running current for a DC motor whose starting resistance is its armature resistance. If not controlled, this value of current would obviously burn up the motor winding insulation and exert excessive acceleration forces on the rotor.



Picture 19, Starting Current of a Motor

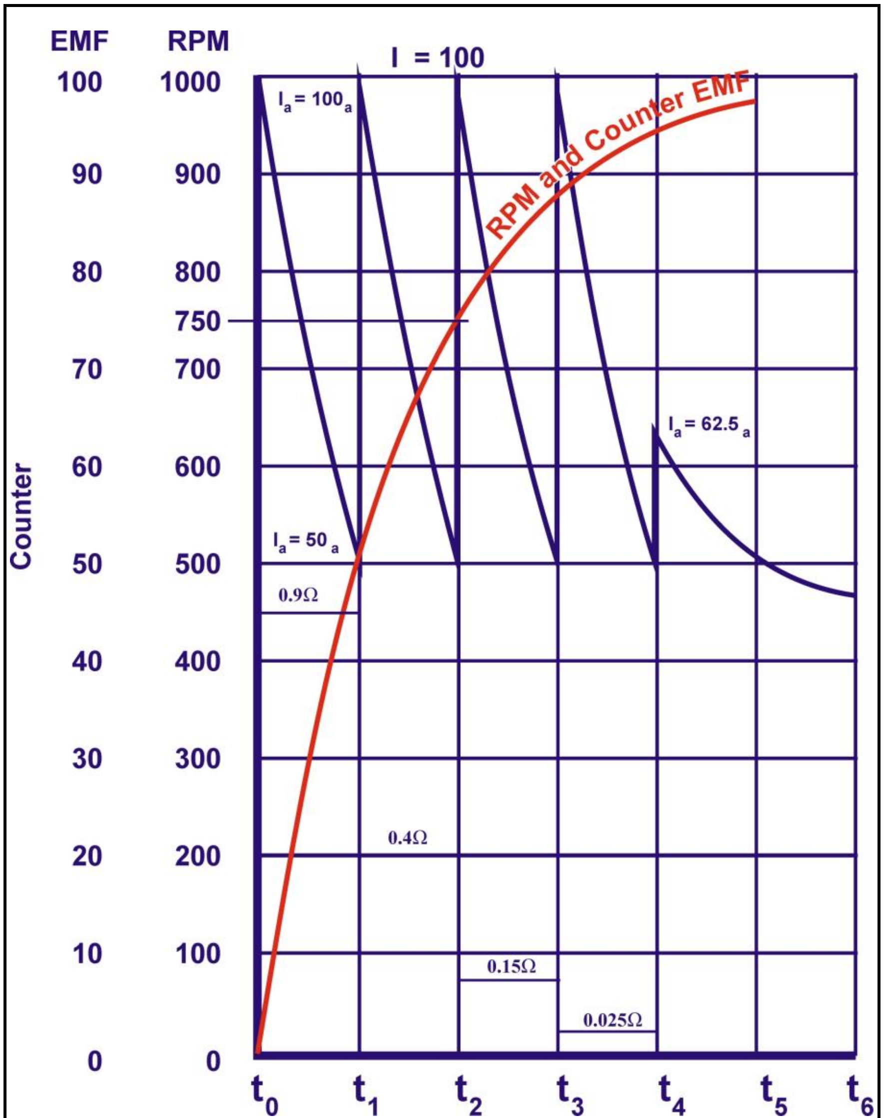
e. To prevent machine damage from high current, such as melting insulation and conductors, and creating excessive shaft torque, it is necessary to employ an external resistance in series with the armature. This will keep starting current within safe values. As the armature begins to turn, counter emf increases. Because counter emf opposes the applied voltage, armature current is reduced. Resistance in series with the armature can then be reduced either manually or automatically. In this way armature current remains high enough to maintain armature torque greater than retarding torque of the load and the motor continues to increase in speed. It also remains low enough to prevent damage to the insulation. This continues until the motor comes up to normal (rated) speed and full voltage is applied across the armature. The relationship between armature current (I_a), applied voltage (E_a), counter emf voltage

(E_c), armature resistance (R_a), and starting resistance (R_s) for a shunt motor is

$$I_R = \frac{E_a - E_c}{R_a + R_s}$$

f. An average safe value of starting current is 5 to 10 times the running current. This means that starting resistance must be sufficient to limit starting current to this value while at the same time developing the required torque. Inadequate torque could prevent the motor form accelerating to its rated speed in the required time.

g. The 100 volt, 0.1 ohm armature resistance motor in Example 2 will not be damaged if starting current remains below 110 amps and it will not stall if armature current remains above 40 amps. Picture 20 shows the relationship between starting current, speed, and counter emf as four starting resistors are alternately inserted to maintain armature current between 40 and 110 amps.



Picture 20, Shunt Motor Starting Curves

h. Initially, starting resistance of 0.9 ohms is inserted in series with the armature resistance of 0.1 ohms. Speed and counter emf voltage are zero and armature current is limited to 100 amps by the armature resistance acting in series with starting resistance.

$$I = \frac{100\text{v}}{0.9\Omega + 0.1\Omega} = \frac{100}{1} = 100\text{amps}$$

i. As the speed increases, counter emf increases. The counter emf subtracts from applied emf, causing armature current to decrease. When speed is 500 rpm the counter emf is 50 volts and the current is 50 amps.

$$I_a = \frac{100-50}{001+0.9} = \frac{50}{1} = 50\,\text{amps}$$

j. At t_1, when the motor speed is 500 rpm, the starting switch is moved to the 0.4Ω tap. Counter emf is 50 volts leaving 50 volts to be applied across the armature, causing armature current to spike up to 100 amps (50 v $\div 0.5\Omega$). Armature speed (and thus counter emf) cannot increase instantly, so speed and counter emf rise gradually during the interval between t_1 and t_2. Armature current decreases gradually and at t_2, when speed is 750 rpm (counter emf of 75 volts), the armature current is 50 amps.

$$I_a = \frac{100-75}{0.1+0.4} = \frac{25}{0.5} = 50\,\text{amps}$$

k. This process continues as the last two starting resistors are substituted until the final resistor is removed and the only resistance in the circuit is armature resistance. The motor continues to increase in speed until effective voltage (E_a-E_2) causes armature current to develop a torque equal to load torque and the motor is running at rated speed.

H. Generator and Motor Efficiency

1. Machine Losses

a. All machines, AC or DC, motor or generator, experience mechanical and electrical losses. One common loss is bearing friction. This can be reduced by using high grade bearings and by providing proper lubrication. Windage loss is loss due to friction between air or another gas and a rapidly revolving rotor. Another loss is iron loss which includes eddy-current and hysteresis losses. A major loss is copper loss (I^2R) described as energy given up as heat in the armature and field windings.

2. Machine Efficiency

   a. The efficiency (η) of any type of machine is the ratio of the output power to the input power. These must be expressed in the same units. This ratio is commonly expressed as a percent. Because all machines have some losses, efficiency will never be 100 percent. Expressed as a percentage, machine efficiency becomes

$$\eta = \frac{\text{output}}{\text{input}} \text{x}100$$

3. Generator Efficiency

   a. The prime mover must supply the power necessary to generate the output and overcome losses. Efficiency is the output divided by the power from the prime mover. Expressed as as a percentage, generator efficiency becomes

$$\eta_G = \frac{\text{output}}{\text{input}} \text{x}100$$

4. Motor Efficiency

   a. As motor losses increase, output decreases by the amount of losses. Therefore, the output of the motor is the difference between the input and the losses. Efficiency is then the output divided by input power. Expressed as a percentage, motor efficiency becomes

$$\eta_m = \frac{\text{input} - \text{losses}}{\text{input}} \text{x}100$$

I. SUMMARY

1. The use of DC motors and generators is generally limited to emergency and high priority systems in commercial nuclear power plants. Reasons for their limited use are expense and maintenance problems associated with the use of brushes, starting circuits, and commutators. This problem does not exist in AC machines. The reason for their use in emergency and high priority systems is that they are powered from (or supply power to) a completely independent highly reliable electrical distribution system (batteries). In low accessibility areas, such as the drywell, DC motors are not used on emergency systems due to the frequent maintenance required. Instead, AC motors powered from more reliable AC buses are used.

2. In a generator, relative motion is set up between the armature and magnetic field. This induces a voltage in the armature. The rotor is the rotating part of the generator, the stator is the stationary part and the armature can be the rotor (rotating armature generator) or the stator (rotating field generator).

3. In a rotating armature DC generator, a single loop armature produces a pulsating DC voltage unsuitable for most DC applications. By providing more individual armature coils, brushes tap off a less varying signal, thereby, reducing ripple. If enough coils are added, ripple becomes almost undetectable and generator output is essentially steady DC.

4. Many losses occur in a generator. I^2R losses are due to resistance of the generator of the generator windings. This loss can be minimized by constructing the generator with the proper diameter and length of copper wire for its designed use. Another form of generator loss is eddy currents. As the generator's magnetic flux changes, it cuts the iron components in the generator (such as the rotor). This induces currents which alternate through the iron and produce heat. Eddy currents are kept to a low value by

laminating the rotor core into many sections and isolating iron components inside the generator. Hysteresis loss occurs when magnetic domains rotate with the alternating magnetic field.

5. This loss produces heat and can be minimized by constructing the generator from a metal with small opposition to domain realignment while retaining its strength.

6. Any loaded generator also meets the requirements for a motor. As the load of a generator increases, this motor action makes the prime mover work harder to maintain a set rpm. If the generator is unloaded, there is essentially no motor action and the prime mover must perform little work to maintain generator rotor speed.

7. The main field of a generator can be produced from an external DC source, called the exciter, or from the generator itself. In either case, this field must be controlled (regulated) because terminal voltage will vary with load changes if the main field strength is maintained constant. This regulation can take place either manually or automatically depending upon the use of the generator.

8. DC motors are basically DC generators which have been motorized by applying voltage to the output terminals. Instead of converting AC current to DC, the commutator of a motor takes DC current and reverses it in each armature coil each time the center of a coil passes under a main field pole. This produced a magnet-motive force which repels the rotor from the field pole. The force acting upon the rotor is called torque and is dependent upon two variables, rotor current and field strength, and fixed design factors, the number of armature conductors and main field poles. If developed torque is greater than load torque, motor speed increases. If developed torque is less than load torque, the motor will slow down. If developed torque equals load torque, motor speed remains constant. Most motors are rated in

horsepower. Horsepower of a motor is dependent upon its speed and torque. A 10 hp motor can develop a lot of torque at a slow speed or rotate at higher speed but develop little torque. The largest use for DC motors in a nuclear power plant is for accessible loads in emergency or vital systems. Because of high maintenance requirements, DC motors are not normally used in limited access or unaccessible areas.

9. ny operating motor meets all the requirements of a generator. The generated voltage is in opposition to the applied voltage and lowers the effective voltage across the armature. This counter voltage is at maximum value when the motor is at rated speed. The resultant motor current, due to the effective armature voltage and armature resistance, is running current.

10. When voltage is applied to the terminals of a stationary motor, no counter voltage is produced to reduce the effective armature voltage. Because armature resistance is kept low by design and effective armature voltage is equal to applied voltage, high currents will be developed which will damage the motor due to excessive heating and torque. Starting resistors are used in series with armature windings. These maintain resistance high enough to limit starting current to some safe value, 5 to 10 times running current, while at the same time maintaining developed torque high enough to allow the motor to accelerate. Once the motor reaches rated speed, it develops sufficient counter emf to reduce effective armature voltage and armature current to some acceptable value. These starting resistors are not left in the circuit and are used only while the motor is being started.

11. All machines have losses, both mechanical and electrical, including: I^2R, hysteresis, eddy current, and windage losses. Because efficiency is the ratio of its output to input, all machines will have an efficiency some what less than one (unity).

PRACTICE:

1 What are dynamos?

2. What is a generator?