DOE Fundamentals

ELECTRICAL SCIENCE

Module 10

AC Generators

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REFERENCES

- Gussow, Milton, Schaum's Outline of Basic Electricity, 2nd Edition, McGraw-Hill.
- Academic Program for Nuclear Power Plant Personnel, Volume I & II, Columbia, MD: General Physics Corporation, Library of Congress Card #A 326517, 1982.
- Nasar and Unnewehr, Electromechanics and Electric Machines, 2nd Edition, John Wiley and Sons.
- Nooger and Neville Inc., Van Valkenburgh, Basic Electricity, Vol. 5, Hayden Book Company.
- Lister, Eugene C., Electric Circuits and Machines, 5th Edition, McGraw-Hill.
- Croft, Hartwell, and Summers, American Electricians' Handbook, 16th Edition, McGraw-Hill.
- Mason, C. Russell, The Art and Science of Protective Relaying, John Wiley and Sons.
- Mileaf, Harry, Electricity One - Seven, Revised 2nd Edition, Prentice Hall.
- Kidwell, Walter, Electrical Instruments and Measurements, McGraw-Hill.
- Buban and Schmitt, Understanding Electricity and Electronics, 3rd Edition, McGraw-Hill.

OBJECTIVES

TERMINAL OBJECTIVE

1.0 Given the type and application of an AC generator, **DESCRIBE** the operating characteristics of that generator including methods of voltage production, advantages of each type, and methods for paralleling.

ENABLING OBJECTIVES

1.1 **STATE** the purpose of the following components of an AC generator:

a. Field

b. Armature

c. Prime mover

d. Rotor

e. Stator

f. Slip rings

1.2 Given the speed of rotation and number of poles, **CALCULATE** the frequency output of an AC generator.

1.3 **LIST** the three losses found in an AC generator.

1.4 Given the prime mover input and generator output, **DETERMINE** the efficiency of an AC generator.

1.5 **DESCRIBE** the bases behind the kW and current ratings of an AC generator.

1.6 **DESCRIBE** the conditions that must be met prior to paralleling two AC generators including consequences of not meeting these conditions.

1.7 **DESCRIBE** the difference between a stationary field, rotating armature AC generator and a rotating field, stationary armature AC generator.

1.8 **EXPLAIN** the differences between a wye-connected and delta-connected AC generator including advantages and disadvantages of each type.

AC GENERATOR COMPONENTS

AC generators are widely used to produce AC voltage. To understand how these generators operate, the function of each component of the generator must first be understood.

EO 1.1 STATE the purpose of the following components of an AC generator:

a. Field
b. Armature
c. Prime mover
d. Rotor
e. Stator
f. Slip rings

Field

The *field* in an AC generator consists of coils of conductors within the generator that receive a voltage from a source (called excitation) and produce a magnetic flux. The magnetic flux in the field cuts the armature to produce a voltage. This voltage is ultimately the output voltage of the AC generator.

Armature

The *armature* is the part of an AC generator in which voltage is produced. This component consists of many coils of wire that are large enough to carry the full-load current of the generator.

Prime Mover

The *prime mover* is the component that is used to drive the AC generator. The prime mover may be any type of rotating machine, such as a diesel engine, a steam turbine, or a motor.

Rotor

The *rotor* of an AC generator is the rotating component of the generator, as shown in Figure 1. The rotor is driven by the generator's prime mover, which may be a steam turbine, gas turbine, or diesel engine. Depending on the type of generator, this component may be the armature or the field. The rotor will be the armature if the voltage output is generated there; the rotor will be the field if the field excitation is applied there.

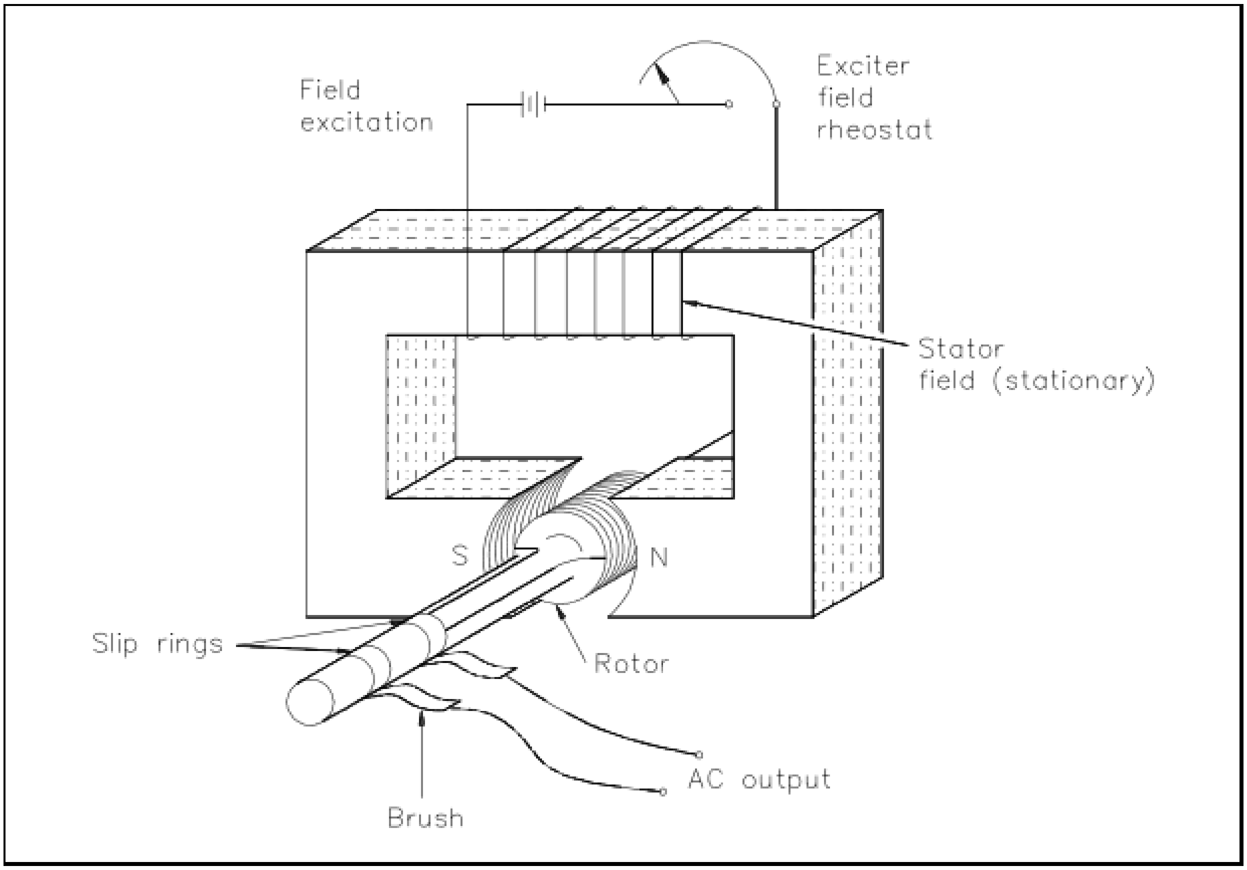

Figure 1 Basic AC Generator

Stator

The *stator* of an AC generator is the part that is stationary (refer to Figure 1). Like the rotor, this component may be the armature or the field, depending on the type of generator. The stator will be the armature if the voltage output is generated there; the stator will be the field if the field excitation is applied there.

Slip Rings

Slip rings are electrical connections that are used to transfer power to and from the rotor of an AC generator (refer to Figure 1). The slip ring consists of a circular conducting material that is connected to the rotor windings and insulated from the shaft. Brushes ride on the slip ring as the rotor rotates. The electrical connection to the rotor is made by connections to the brushes.

Slip rings are used in AC generators because the desired output of the generator is a sine wave. In a DC generator, a commutator was used to provide an output whose current always flowed in the positive direction, as shown in Figure 2. This is not necessary for an AC generator. Therefore, an AC generator may use slip rings, which will allow the output current and voltage to oscillate through positive and negative values. This oscillation of voltage and current takes the shape of a sine wave.

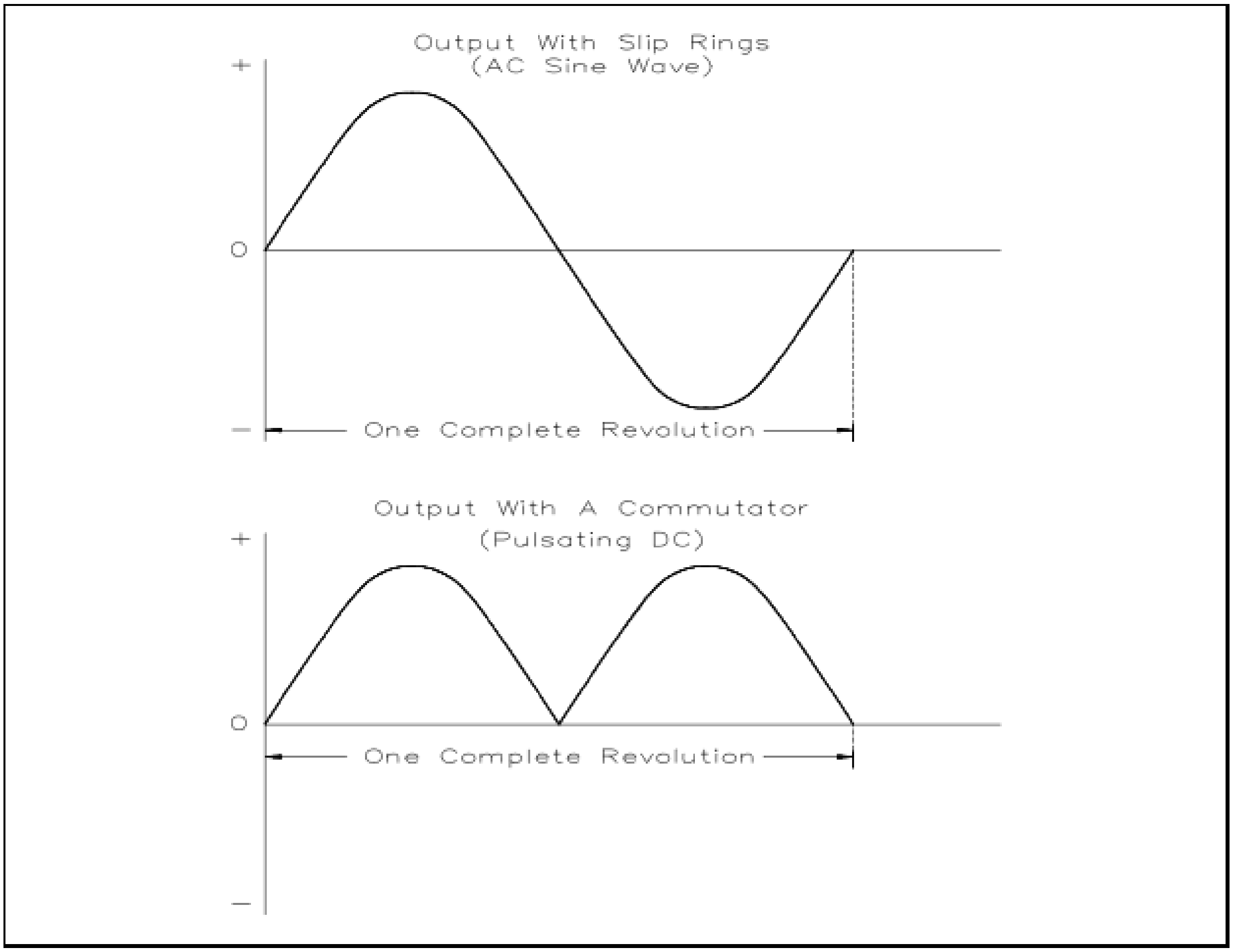

Figure 2 – Comparison of DC and AC Generator Outputs

Summary

The important information in this chapter is summarized below.

AC Generator Components Summary

- The field in an AC generator consists of coils of conductors within the generator that receive a voltage from a source (called excitation) and produce a magnetic flux.
- The armature is the part of an AC generator in which output voltage is produced.
- The prime mover is the component that is used to drive the AC generator.
- The rotor of an AC generator is the part that is driven by the prime mover and that rotates.
- The stator of an AC generator is the part that is stationary.
- Slip rings are electrical connections that are used to transfer power to and from the rotor of an AC generator.

AC GENERATOR THEORY

AC generators are widely used to produce AC voltage. To understand how these generators operate, the basic theory of operation must first be understood.

EO 1.2 Given the speed of rotation and number of poles, **CALCULATE** the frequency output of an AC generator.

EO 1.3 **LIST** the three losses found in an AC generator.

EO 1.4 Given the prime mover input and generator output, **DETERMINE** the efficiency of an AC generator.

Theory of Operation

A simple AC generator consists of: (a) a strong magnetic field, (b) conductors that rotate through that magnetic field, and (c) a means by which a continuous connection is provided to the conductors as they are rotating (Figure 3). The strong magnetic field is produced by a current flow through the field coil of the rotor. The field coil in the rotor receives excitation through the use of slip rings and brushes. Two brushes are spring-held in contact with the slip rings to provide the continuous connection between the field coil and the external excitation circuit. The armature is contained within the windings of the stator and is connected to the output. Each time the rotor makes one complete revolution, one complete cycle of AC is developed. A generator has many turns of wire wound into the slots of the rotor.

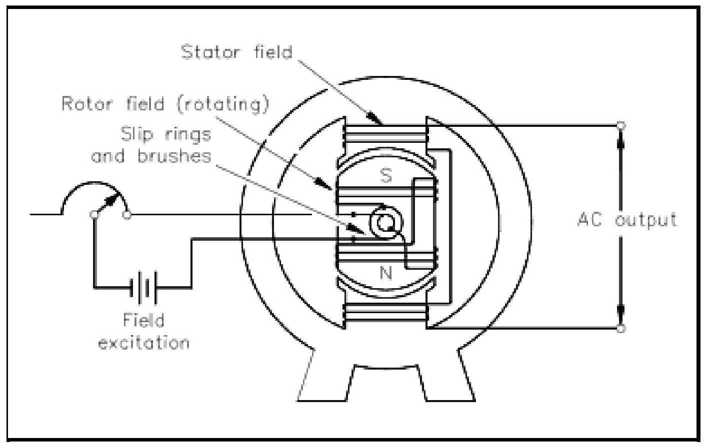

Figure 3 Simple AC Generator

The magnitude of AC voltage generated by an AC generator is dependent on the field strength and speed of the rotor. Most generators are operated at a constant speed; therefore, the generated voltage depends on field excitation, or strength.

The frequency of the generated voltage is dependent on the number of field poles and the speed at which the generator is operated, as indicated in Equation (10-1).

$$f = \frac{N\,P}{120} \qquad (10\text{-}1)$$

where

f = frequency (Hz)

P	=	total number of poles
N	=	rotor speed (rpm)
120	=	conversion from minutes to seconds and from poles to pole pairs

The 120 in Equation (10-1) is derived by multiplying the following conversion factors.

$$\frac{60 \text{ seconds}}{1 \text{ minute}} \times \frac{2 \text{ poles}}{\text{pole pair}}$$

In this manner, the units of frequency (hertz or cycles/sec.) are derived.

Losses in an AC Generator

The load current flows through the armature in all AC generators. Like any coil, the armature has some amount of resistance and inductive reactance. The combination of these make up what is known as the *internal resistance,* which causes a loss in an AC generator. When the load current flows, a voltage drop is developed across the internal resistance. This voltage drop subtracts from the output voltage and, therefore, represents generated voltage and power that is lost and not available to the load. The voltage drop in an AC generator can be found using Equation (10-2).

$$\text{Voltage drop} = I_aR_a + I_aX_{La} \qquad (10\text{-}2)$$

where

I_a	=	armature current
R_a	=	armature resistance
X_{La}	=	armature inductive reactance

Hysteresis Losses

Hysteresis losses occur when iron cores in an AC generator are subject to effects from a magnetic field. The magnetic domains of the cores are held in alignment with the field in varying numbers, dependent upon field strength. The magnetic domains rotate, with respect to the domains not held in alignment, one complete turn during each rotation of the rotor. This rotation of magnetic domains in the iron causes friction and heat. The heat produced by this friction is called magnetic hysteresis loss.

To reduce hysteresis losses, most AC armatures are constructed of heat-treated silicon steel, which has an inherently low hysteresis loss. After the heat-treated silicon steel is formed to the desired shape, the laminations are heated to a dull red and then allowed to cool. This process, known as annealing, reduces hysteresis losses to a very low value.

Mechanical Losses

Rotational or *mechanical losses* can be caused by bearing friction, brush friction on the commutator, and air friction (called windage), which is caused by the air turbulence due to armature rotation. Careful maintenance can be instrumental in keeping bearing friction to a minimum. Clean bearings and proper lubrication are essential to the reduction of bearing friction. Brush friction is reduced by ensuring: proper brush seating, proper brush use, and maintenance of proper brush tension. A smooth and clean commutator also aids in the reduction of brush friction. In very large generators, hydrogen is used within the generator for cooling; hydrogen, being less dense than air, causes less windage losses than air.

Efficiency

Efficiency of an AC generator is the ratio of the useful power output to the total power input. Because any mechanical process experiences some losses, no AC generators can be 100 percent efficient. Efficiency of an AC generator can be calculated using Equation (10-3).

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100 \qquad (10\text{-}3)$$

Example: Given a 5 hp motor acting as the prime mover of a generator that has a load demand of 2 kW, what is the efficiency of the generator?

Solution:

In order to calculate efficiency, the input and output power must be in the same units. As described in Thermodynamics, the horsepower and the watt are equivalent units of power.

Therefore, the equivalence of these units is expressed with a conversion factor as follows.

$$\left\{\frac{550\ \frac{\text{ft}-\text{lbf}}{\text{sec}}}{1\ \text{hp}}\right\}\left\{\frac{1\ \text{kw}}{737.6\ \frac{\text{ft}-\text{lbf}}{\text{sec}}}\right\}\left\{\frac{1000\ \text{w}}{1\ \text{kw}}\right\} = 746\ \frac{\text{w}}{\text{hp}}$$

Input Power = $5\ \text{hp} \times 746\ \frac{\text{w}}{\text{hp}} = 3730\ \text{w}$

Output Power = $2\ \text{kw} = 2000\ \text{w}$

Efficiency = $\frac{\text{Output}}{\text{Input}} = \frac{2000\ \text{w}}{3730\ \text{w}} = 0.54 \times 100 = 54\%$

Summary

The important information covered in this chapter is summarized below.

AC Generator Theory Summary

- The frequency of the generated voltage in an AC generator can be calculated by multiplying the number of poles by the speed of the generator and dividing by a factor of 120.
- The three losses found in an AC generator are:
  - Internal voltage drops due to the internal resistance and impedance of the generator
  - Hysteresis losses
  - Mechanical losses
- Efficiency of an AC generator can be calculated by dividing the output by the input and multiplying by 100.

AC GENERATOR OPERATION

Because of the nature of AC voltage and current, the operation of an AC generator requires that rules and procedures be followed. In addition, there are various types of AC generators available, each type having advantages and disadvantages.

EO 1.5 DESCRIBE the bases behind the kW and current ratings of an AC generator.

EO 1.6 DESCRIBE the conditions that must be met prior to paralleling two AC generators including consequences of not meeting these conditions.

EO 1.7 DESCRIBE the difference between a stationary field, rotating armature AC generator and a rotating field, stationary armature AC generator.

EO 1.8 EXPLAIN the differences between a wye-connected and delta-connected AC generator including advantages and disadvantages of each type.

Ratings

Typical name plate data for an AC generator (Figure 4) includes: (1) manufacturer; (2) serial number and type number; (3) speed (rpm), number of poles, frequency of output, number of phases, and maximum supply voltage; (4) capacity rating in KVA and kW at a specified power factor and maximum output voltage; (5) armature and field current per phase; and (6) maximum temperature rise.

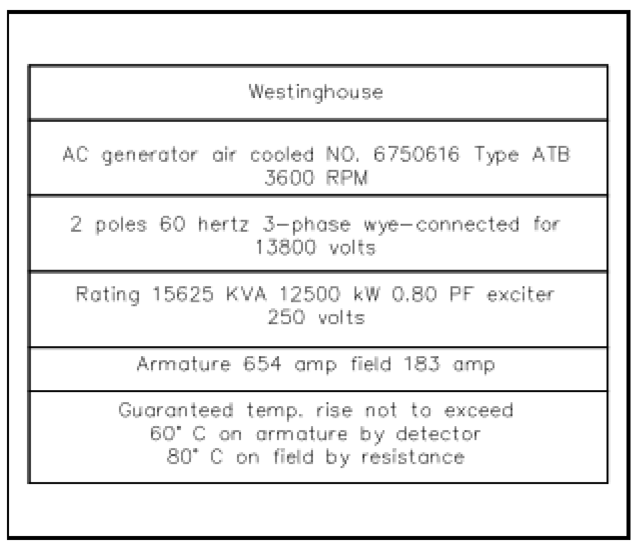

Figure 4 AC Generator Nameplate Ratings

Power (kW) ratings of an AC generator are based on the ability of the prime mover to overcome generator losses and the ability of the machine to dissipate the internally generated heat. The current rating of an AC generator is based on the insulation rating of the machine.

Paralleling AC Generators

Most electrical power grids and distribution systems have more than one AC generator operating at one time. Normally, two or more generators are operated in parallel in order to increase the available power. Three conditions must be met prior to paralleling (or synchronizing) AC generators.

- Their terminal voltages must be equal. If the voltages of the two AC generators are not equal, one of the AC generators could be picked up as a reactive load to the other AC generator. This causes high currents to be exchanged between the two machines, possibly causing generator or distribution system damage.
- Their frequencies must be equal. A mismatch in frequencies of the two AC generators will cause the generator with the lower frequency to be picked up as a load on the other generator (a condition referred to as "motoring"). This can cause an overload in the generators and the distribution system.
- Their output voltages must be in phase. A mismatch in the phases will cause large opposing voltages to be developed. The worst case mismatch would be 180° out of phase, resulting in an opposing voltage between the two generators of twice the output voltage. This high voltage can cause damage to the generators and distribution system due to high currents.

During paralleling operations, voltages of the two generators that are to be paralleled are indicated through the use of voltmeters. Frequency matching is accomplished through the use of output frequency meters. Phase matching is accomplished through the use of a synchroscope, a device that senses the two frequencies and gives an indication of phase differences and a relative comparison of frequency differences.

Types of AC Generators

As previously discussed, there are two types of AC generators: the stationary field, rotating armature; and the rotating field, stationary armature.

Small AC generators usually have a stationary field and a rotating armature (Figure 5). One important disadvantage to this arrangement is that the slip-ring and brush assembly is in series with the load circuits and, because of worn or dirty components, may interrupt the flow of current.

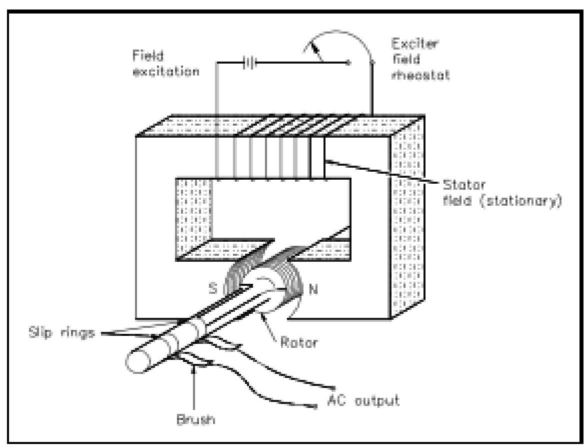

Figure 5 Stationary Field,
Rotating Armature AC Generator

If DC field excitation is connected to the rotor, the stationary coils will have AC induced into them (Figure 6). This arrangement is called a rotating field, stationary armature AC generator.

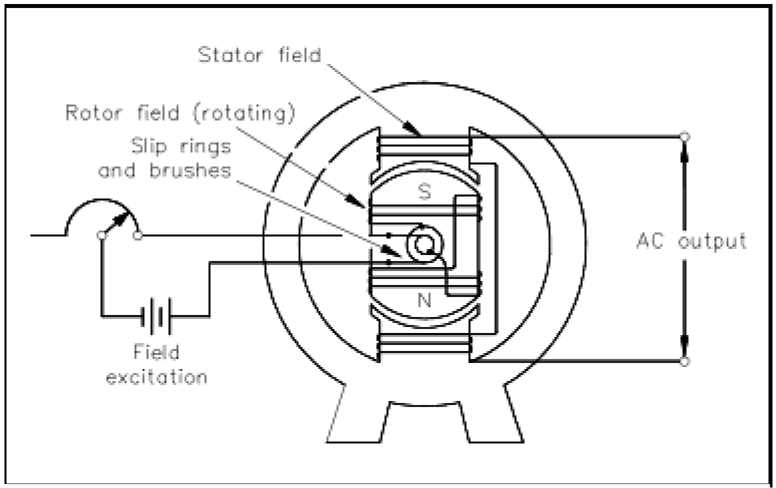

Figure 6 Simple AC Generator - Rotating Field, Stationary Armature

The rotating field, stationary armature type AC generator is used when large power generation is involved. In this type of generator, a DC source is supplied to the rotating field coils, which produces a magnetic field around the rotating element. As the rotor is turned by the prime mover, the field will cut the conductors of the stationary armature, and an EMF will be induced into the armature windings.

This type of AC generator has several advantages over the stationary field, rotating armature AC generator: (1) a load can be connected to the armature without moving contacts in the circuit; (2) it is much easier to insulate stator fields than rotating fields; and (3) much higher voltages and currents can be generated.

Three-Phase AC Generators

The principles of a three-phase generator are basically the same as that of a single-phase generator, except that there are three equally-spaced windings and three output voltages that are all 120° out of phase with one another. Physically adjacent loops (Figure 7) are separated by 60° of rotation; however, the loops are connected to the slip rings in such a manner that there are 120 electrical degrees between phases.

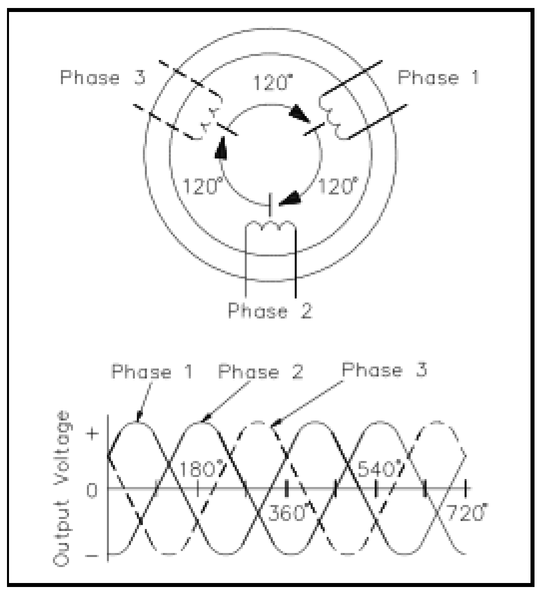

Figure 7 Stationary Armature 3Φ Generator

The individual coils of each winding are combined and represented as a single coil. The significance of Figure 7 is that it shows that the three-phase generator has three separate armature windings that are 120 electrical degrees out of phase.

AC Generator Connections

As shown in Figure 7, there are six leads from the armature of a three-phase generator, and the output is connected to an external load. In actual practice, the windings are connected together, and only three leads are brought out and connected to the external load.

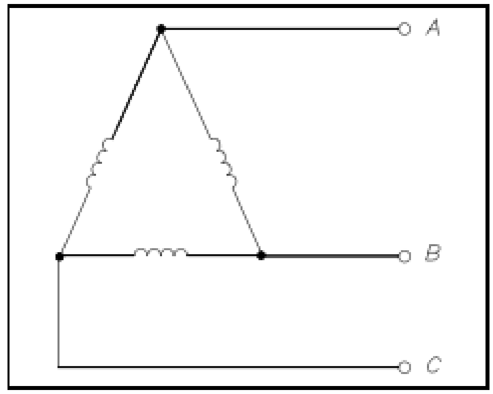

Figure 8 Delta Connection

Two means are available to connect the three armature windings. In one type of connection, the windings are connected in series, or delta-connected (Δ) (Figure 8).

In a delta-connected generator, the voltage between any two of the phases, called line voltage, is the same as the voltage generated in any one phase. As shown in Figure 9, the three phase voltages are equal, as are the three line voltages. The current in any line is V3 times the phase current. You can see that a delta-connected generator provides an increase in current, but no increase in voltage.

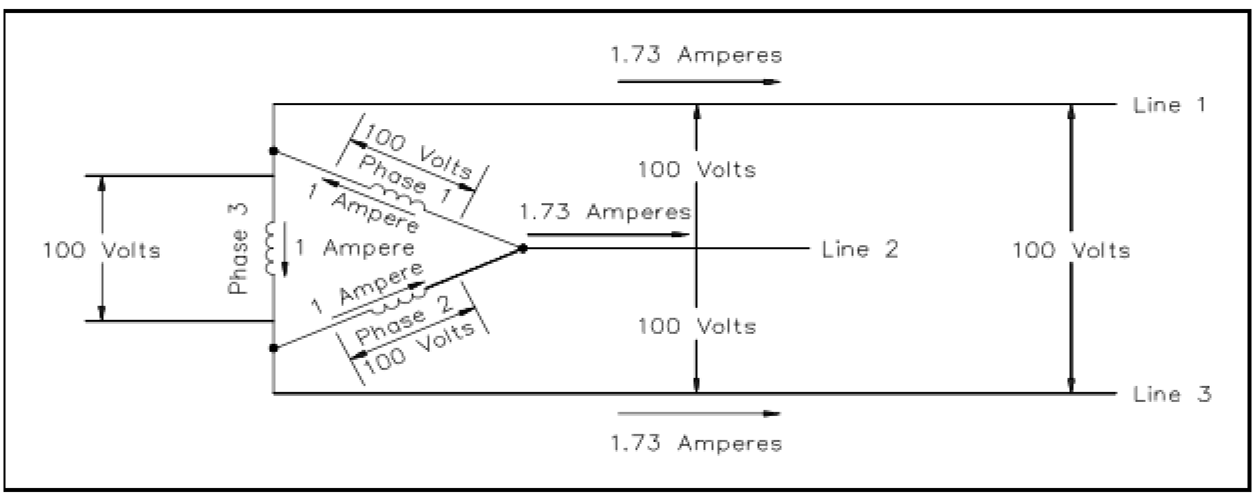

Figure 9 Characteristics of a Delta-Connected Generator

An advantage of the delta-connected AC generator is that if one phase becomes damaged or open, the remaining two phases can still deliver three-phase power. The capacity of the generator is reduced to 57.7% of what it was with all three phases in operation.

In the other type of connection, one of the leads of each winding is connected, and the remaining three leads are connected to an external load. This is called a wye connection (Y) (Figure 10).

The voltage and current characteristics of the wye-connected AC generator are opposite to that of the delta connection. Voltage between any two lines in a wye-connected AC generator is 1.73 (or $\sqrt{3}$) times any one phase voltage, while line currents are equal to phase currents. The wye-connected AC generator provides an increase in voltage, but no increase in current (Figure 11).

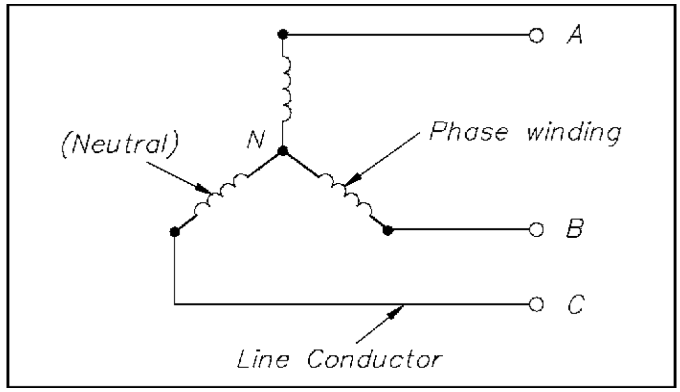

Figure 10 Wye Connection

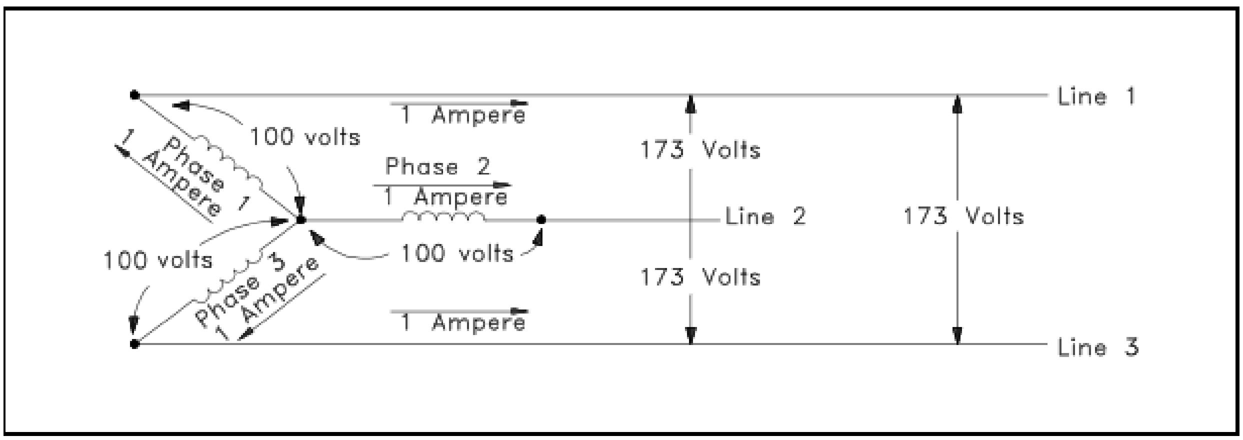

Figure 11 Characteristics of a Wye-Connected AC Generator

An advantage of a wye-connected AC generator is that each phase only has to carry 57.7% of line voltage and, therefore, can be used for high voltage generation.

Summary

The important information covered in this chapter is summarized below.

AC Generator Operation Summary

- Power (kW) ratings of an AC generator are based on the ability of the prime mover to overcome generation losses and the ability of the machine to dissipate the heat generated internally. The current rating of an AC generator is based on the insulation rating of the machine.
- There are three requirements that must be met to parallel AC generators:
  1) Their terminal voltages must be equal. A mismatch may cause high currents and generator or distribution system damage.
  2) Their frequencies must be equal. A mismatch in frequencies can cause one generator to "motor," causing an overload in the generators and the distribution system.
  3) Their output voltages must be in phase. A mismatch in the phases will cause large opposing voltages to be developed, resulting in damage to the generators and distribution system due to high currents.
- The disadvantage of a stationary field, rotating armature is that the slip-ring and brush assembly is in series with the load circuits and, because of worn or dirty components, may interrupt the flow of current.
- A stationary armature, rotating field generator has several advantages: (1) a load can be connected to the armature without moving contacts in the circuit; (2) it is much easier to insulate stator fields than rotating fields; and (3) much higher voltages and currents can be generated.
- The advantage of the delta-connected AC generator is that if one phase becomes damaged or open, the remaining two phases can still deliver three-phase power at a reduced capacity of 57.7%.
- The advantage of a wye-connected AC generator is that each phase only has to carry 57.7% of line voltage and, therefore, can be used for high voltage generation.