Principals of AC Generators

A. Principles of AC Generators

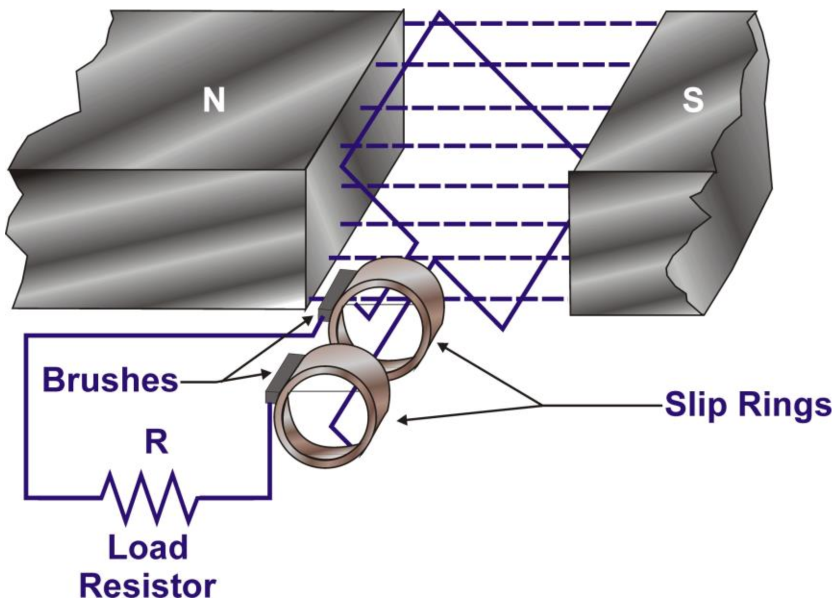
1. Commercial Power Generation

   a. Alternating current has definite advantages over direct current. Low voltage DC cannot be transmitted economically over long distances due to considerable transmission line power loss resulting from large heat (I^2R) losses. AC power, however, can be transmitted over greater distances (for example, Canada to New York) without appreciable loss. AC has the ability to be easily converted to high voltage, low current at its source. It is transmitted at this low current value (low I^2R losses) to the load, and reconverted to its required current and voltage. Notice that power remains the same throughout the conversion process, P = I9E8pf. The process of converting AC voltage and current is called transformation. It is performed by electrical transformers discussed later. Because of this unique ability, most electrical power for commercial use is generated by AC generators.

2. Comparison of Basic AC and DC Generators

   a. All generators operate on the same basic principles. To generate a voltage, a conductor must be in a magnetic field with relative motion between the two. Stator and rotor each have a distinct set of windings. Voltage is induced in one winding (armature) and the other produces a magnetic field. If DC excitation is applied to the stator and power removed from the rotor, it is a rotating armature generator. On the other hand, if DC excitation is applied to the rotor and power removed from the stator, it is a rotating field generator. The rotor of a generator may be driven by any one of a number of commonly used prime movers, such as turbines (gas, water, or steam), electric motors, or an internal combustion engine.

b. The main difference between AC and DC machines, both generators and motors, is that AC machines use slip rings, sometimes called collector rings. Since the slip rings used in AC machines are very smooth when compared to the commutator of a DC machine, brushes last much longer. Therefore, many maintenance problems found in DC machines are avoided. The simple generator used to produce AC output is shown Picture-1.



Picture 1, Simple 2-Pole AC Generator

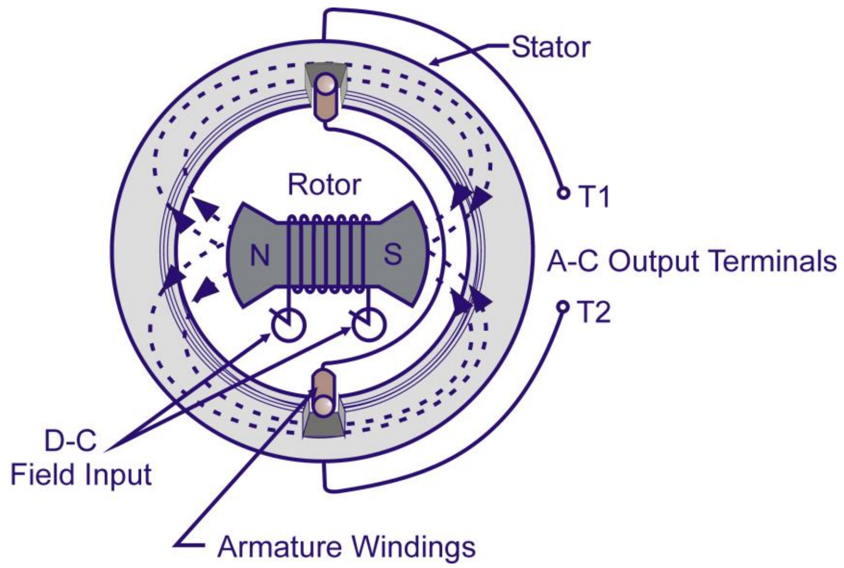
3. Rotating Armature Generator

a. The stator of a rotating armature AC generator provides a stationary electromagnetic field. The rotor, acting as an armature, revolves in the field, cutting lines of force set up by the stator and producing desired output voltage. In this generator, armature output is taken through slip rings via brushes and retains its alternating characteristic. The disadvantage of taking output from the armature is that full power supplied by the generator must pass through the slip ring/brush interface. Because this interface has a greater resistance than a single fixed conductor, heat losses (I^2R) and arcing may become excessive as power delivered increases. The simple AC generator discussed previously was a revolving armature generator.

b. The armature coil is wound in slots in the armature core. The pole pieces are made of soft iron. Because magnetic lines of force will travel much more readily through soft iron than through air, these pole pieces concentrate magnetic flux of the field magnet near the armature. Thus, the magnetic field cut by the armature coil is increased and, as a result, induced voltage is greater than if the pole pieces were removed and air separated the field magnet and the armature. For simple, low-current purposes, the magneto described above may be suitable. Where large amounts of current are required, electromagnets instead of permanent magnets are used to produce the necessary magnetic field. Not only can stronger magnetic fields be obtained by electromagnets but the field strength can easily be controlled by varying current flow. Since a steady magnetic field is required, direct current must be sent through the electromagnet. This direct current may be obtained from storage batteries, but is usually supplied by the generator output (self-excitation) This direct current for the field is called the excitation current and is supplied by an exciter.

4. Rotating Field Generator

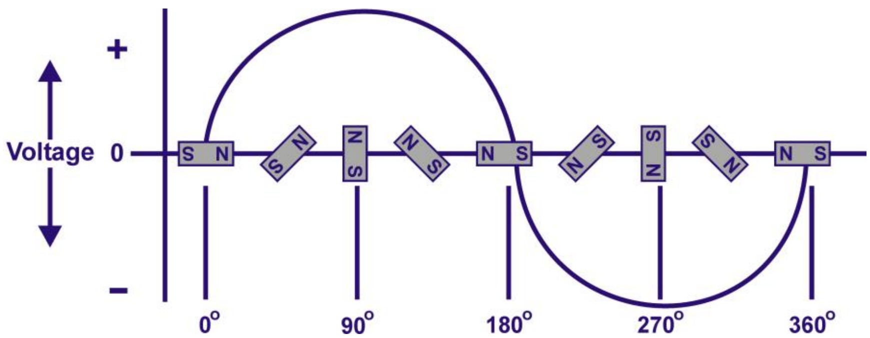
5. Picture-2 shows a rotating field generator which is by far the most widely used type of AC generator.



Picture 2, Simple Rotating Field AC Generator

6. In this type generator, direct current is passed through windings on the rotor by means of slip rings and brushes. This maintains a rotating electromagnetic field of fixed polarity, similar to a rotating bar magnet, which can also be used. The rotating magnetic field, following the turning of the rotor, extends outward and cuts through armature windings embedded in the surrounding stator. As the rotor turns, alternating voltages are induced in the windings because a magnetic field of first one polarity and then the other cuts through them. Because output power is taken from stationary windings, the output may be connected through fixed terminals directly to external loads, as through terminals T1 and T2 in Picture-4. This is advantageous as there are no high resistance sliding contacts for output power and the whole output circuit is continuously insulated. This minimizes the danger of arc-over. Because of the relatively low power level in the field, slip rings and brushes are used on the rotor to supply DC to field

windings without adverse wear and sparking. Picture-5 shows the sine wave developed as a function of rotor (magnet) position for a rotating field type AC generator.



Picture 3, Sine Wave Produced by a Rotating Field AC Generator

B. Three Phase AC Generators

1. Single Phase Generator Frequency

   a. The output frequency of an AC generator depends upon the speed of rotor rotation and the number of magnetic poles. As speed increases, frequency increases. More poles on the rotor also increases frequency. A 2-pole generator would need to rotate at twice the speed of a 4-pole generator to produce the same frequency. These two principles were used previously to determine frequency.

   b. Example: If a 2-pole generator and a 4-pole generator were both required to produce 60 Hz, what would each generator's required rotor speed be?

   c. Answer:

      1) Solve for the required speed of the 2-pole generator.

$$\text{If } f = \frac{PS}{120}, \text{then } N = \frac{120F}{P} = 120 \text{ x } \frac{60}{2}$$

3600 RPM

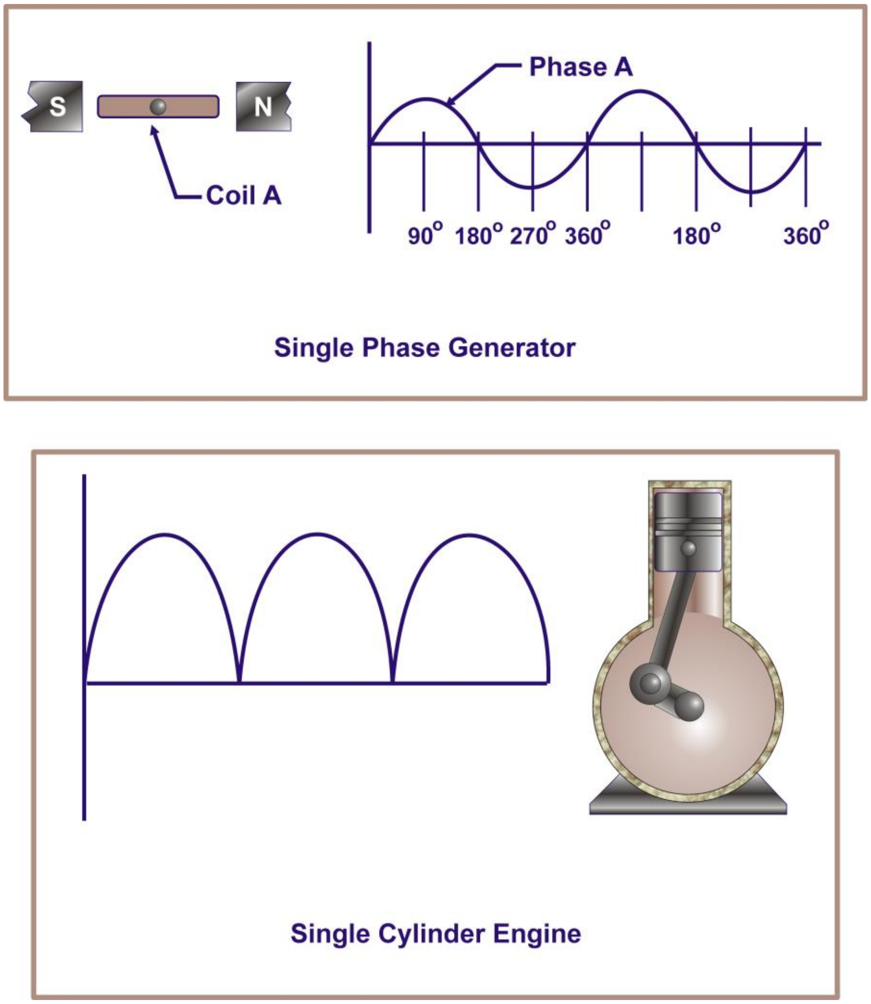
2) Solve for the required speed of the 4-pole generator.

$$N = \frac{120F}{P} = 120\,x\,\frac{60}{2} = 1800\text{rpm}$$

d. All of the AC generators discussed have produced identical cycles of output voltage in a single repeated pattern. These generators are referred to as single phase generators.

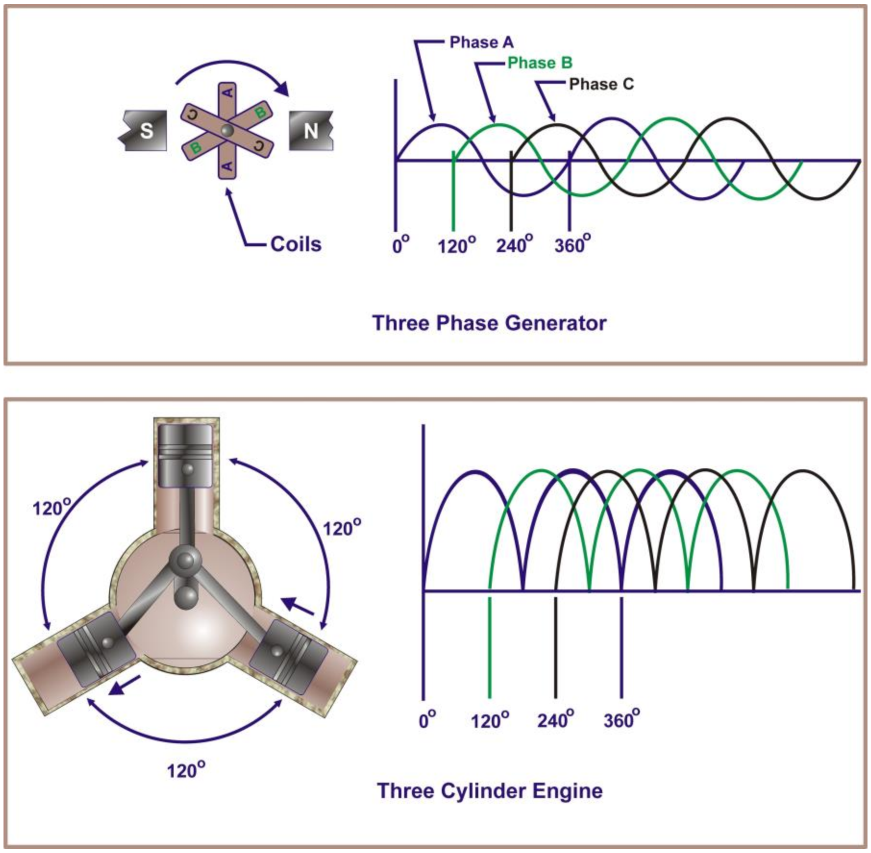
2. Three Phase Generation

a. Like a single cylinder engine, power of a single-phase generator occurs in pulses (Picture-4).



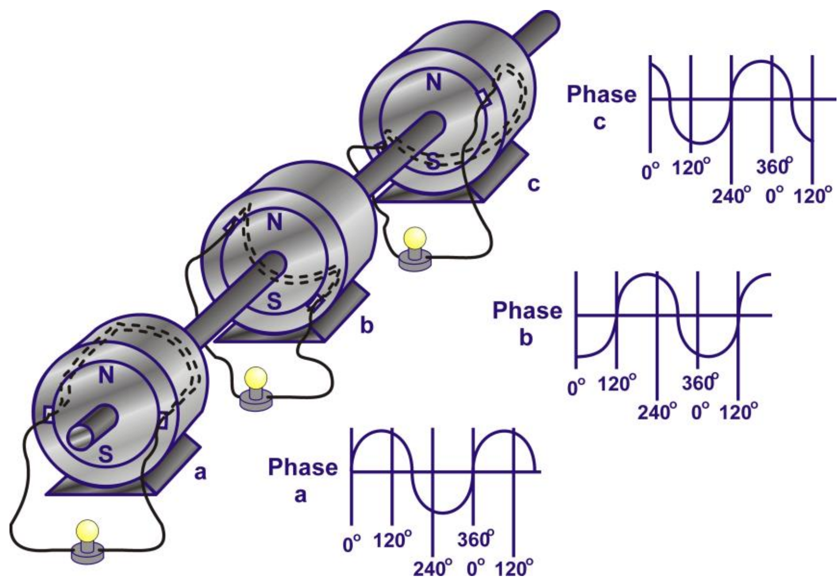
Picture 4, Single Phase Pulsing Power

b. For small power demands this is satisfactory, but for larger power outputs, physical size and pulsing power output become limiting. The pulsing power from gasoline engines can be "smoothed out" by increasing the number of cylinders (Picture-5A). The pulsing characteristic of an AC generator can also be smoothed out and a higher average power produced by increasing the number of separate windings in the armature. This is shown for a rotating armature generator in Picture-5B. Understand that if we wanted to produce the same effect in a rotating field generator, the number of separate armature windings in the stator would be increased.



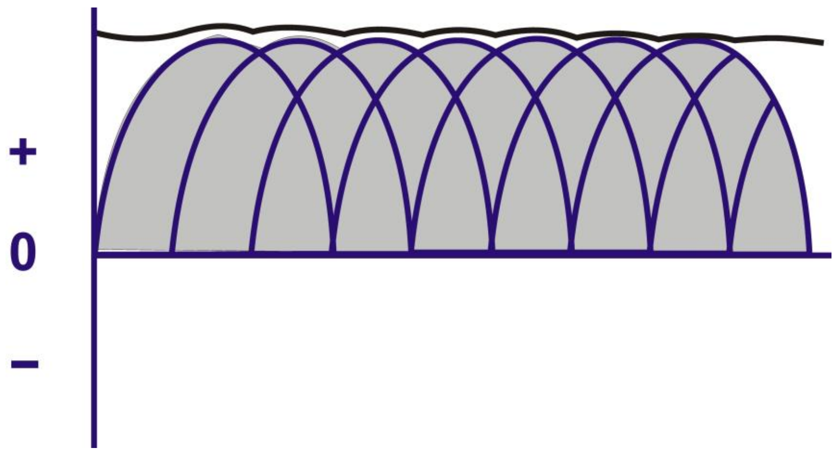
Picture 5, Smoother Power Output (30/)

c. To achieve this higher average power, three single-phase rotating field generators are coupled together on the same drive shaft (Picture-6).



Picture 6, Three Single Phase Generators on a Single Shaft

d. Notice that the North poles are at the top of each rotor. Stator coils (in this case, also the armature coils) of generator "a" are placed in slots identical to the single-phase generator. Stator coils of generator "b" are placed in slots one third of a rotation (120°) counterclockwise from "a". Stator coils of generator "c" are placed in slots two thirds of a revolution (240°) counterclockwise, from "a". As the shaft is rotated counterclockwise, each generator will produce voltage as shown in the sine wave plots for each phase. Because each generator is alike except for coil position, voltages will be of equal peak value and wave shape. However, the time at which each voltage passes through its maximum and zero point, and the time it reverses, is different (not in-phase). Due to the construction of identical stators, the three identical waveshapes are spaced 120° apart. The three single phase generators, if considered as one machine, have become a three-phase generator. Power output of each generator consists of two power pulses each electrical cycle. Since power pulses of each generator occur 120° apart, the combined three phase power output of individual generators consists of six pulses and is much smoother than any single-phase generator alone (Picture-7).



Picture 7, Total Three Phase Power

Picture-7

e. The large size of the generator in Picture-6 would prevent its practical application. Therefore, three windings are placed in the same stator and spaced 120E apart as before. Because all single-phase rotors are identical, a single large rotor of the same design may be used. Electrically there is no change, and although the weight of the new three phase generator is only slightly more than the former single phase generator, it has three times the power output.

3. Three-Phase Power

a. In a single phase AC circuit, real power is equal to $IE\cos\theta$ where cosine θ is the power factor.

b. Power delivered by a balanced 3-phase system is equal to power delivered by each phase. The power equation is of no use to the operator as his instruments indicate line voltage and current. Therefore, to solve for real power, line voltage and current must be used. Line current is equal to the phase current and line voltage is equal to the product of phase voltage and the square root of three. The resulting power equation is:

$$P_t = \sqrt{3}\, IE\cos\theta$$

c. And since the cosine of the phase angle is power factor,

$$P_t = \sqrt{3}\, IEpf$$

d. Example: A three-phase generator at full load has an output of 18,000 volts and 30,000 amperes, with a .97 power factor. What is true power?

e. Answer:

$$P_t = \sqrt{3 IE pf}$$

= 1.73 (18,000)(30,000)(.97)

= 906 Mw

f. To find the apparent and reactive power of a three-phase wye system, include the square root of three due to the line and phase voltage differences.

$$P_a = \sqrt{3 IE}$$

$$P_R = \sqrt{3 IE Sin\theta}$$

g. Three phase systems permit large amounts of power to be transmitted (higher average power) at a lower cost (less cost for materials and less line losses) than single phase systems. When single-phase power is required, a load is connected in parallel between any two phases (three combinations exist). Large three phase motors and inductive devices, such as transformers, are more efficient and less costly than single phase equipment with the same power ratings. All large power systems are designed as three phase systems with customer loads balanced across the three phases as closely as possible.

C. Independent AC Generator Operation

1. Load Effects On Generator Voltage

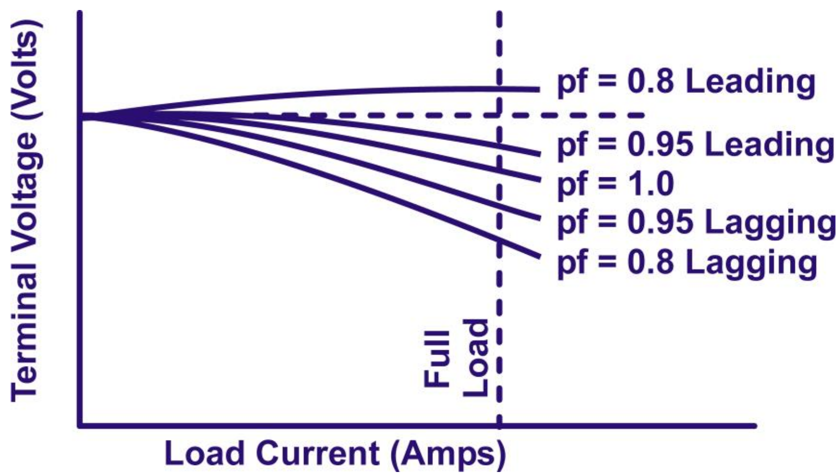
   a. When load on a DC generator increases, terminal voltage drops due to the increase in armature voltage drop and armature reaction. These two effects also occur in an AC generator. Armature reaction in an AC generator may or may not significantly effect terminal voltage. An AC generator has an additional armature voltage drop due to reactance.

   b. As AC generator load increases, current increases proportionally. Therefore, resistive voltage losses (IR) increase at the same rate and magnitude as in the DC generator. However, total opposition to current flow in an AC circuit is the vector sum of the circuit’s, in this case the stator, resistance and reactance (X), which is primarily inductive for a stator. Reactance in an AC generator may be from 30 to 50 times the value of resistance because of relatively large inductance of coils compared with their resistance. This inductive reactance voltage drop (IX_L) is subtracted from generated voltage with remaining voltage applied at the terminals. For a given load increase, the voltage dropped across the armature of the AC generator is greater than for the same load increase on a DC generator.

   c. The principles behind armature reaction in an AC generator are basically the same as a the DC generator. Assume the generator's power factor is unity (1.0) and generator load is increased while maintaining either purely resistive or balanced capacitive and inductive loads. The effect of armature reaction is at a minimum and occurs as in the DC generator.

However, at lagging power factors, the most common operating condition of an AC generator, the magnetizing effect of inductive armature currents oppose the main field's magnetomotive force (mmf), causing an even greater weakening of main field flux. This results in less induced voltage in the stator. The drop in terminal voltage is larger than that which occurred in the DC generator. The more the power factor lags, the more armature mmf demagnetizes the main field. With leading power factors, armature mmf actually aids or strengthens main field mmf, resulting in a higher generated emf with increased load. This magnetizing effect increases as the power factor becomes more leading. Because most power systems usually contain more lagging equipment (e.g., motor, transformers) than leading equipment (e.g., fluorescent lights, high tension wires), power companies often install capacitors to supply some leading reactive demand during heavy load periods to help maintain voltage.

d. When load on an AC generator is changed, terminal voltage varies with load. The amount of variation depends upon the design of the generator and the power factor of the load. When a load has a lagging power factor, the drop in terminal voltage is greater than that for unity power factor (Picture-8). For a load with a leading power factor, terminal voltage tends to rise and, if the leading power factor becomes small enough, may even cause terminal voltage to rise above its original value.



Picture 8, Voltage Regulation Curve of an AC Generator at Various Power Factors

2. AC Generator Voltage Control

   a. In an AC generator, alternating voltage is induced into the armature windings when magnetic fields pass across these windings. Voltage induced into the AC generator windings depends upon three things: the number of conductors in series per winding, the speed at which the magnetic field passes across the winding, and the strength of the magnetic field.

   b. Any of these could conceivably be used to control voltage induced into the AC generator's armature windings. The number of windings is fixed after the generator has been manufactured, so this method is not practical. Also, because the output frequency must remain constant, the speed of the rotating field must be held constant. This prevents use of generator rpm for voltage control. The only practical remaining method for voltage control is regulating the strength of the rotating magnetic field, similar to DC generator voltage control. This is done by the excitation voltage that controls current in the main field windings.

c. Most modern units are equipped with a voltage regulator which can be operated in manual, where the control room operator varies excitation, or in automatic, where an automatic control circuit varies excitation. Automatic regulators are designed to hold main generator voltage at some predetermined adjustable setpoint even under varying generator loads. Reactive power is not affected by an independent generator's main field strength. For an independently operating generator, reactive power demand (VARS) on the generator is determined solely by connected loads.

3. AC Generator Frequency Control

a. Main field speed (output frequency) of a rotating field generator is determined by the speed of its prime mover, the turbine or an engine, which has a speed control system. This may be a mechanical governor or an electronic control circuit designed to maintain the prime mover shaft rotation at a predetermined speed, called the speed setpoint. This setpoint can be adjusted by the control room operator. The normal speed of a generator is that which produces 60 Hz in the generator. If the rotor of a rotating field generator has four poles and must produce 60 Hz, its prime mover must turn at 1800 rpm.

b. When a generating unit is operating independently, the speed control mechanism causes the prime mover speed to change and frequency output of the generator will change. True power output depends upon customer demand only. If more load is added, the speed control mechanism increases prime mover output. Eventually, it will reach maximum power. Additional load causes the generator- power mover unit to slow down. Frequency decreases, and damage may occur to the unit.

c. The generator supplies customer loads instantaneously. If a load increase is assumed, this causes increased motor action in the generator. Subsequently, the generator and its prime mover slow down, allowing frequency to decrease, because the generator requires more power than is being supplied by its prime mover. As the shaft slows, the speed control system increases the power output of the prime mover until the power matches the demand from the generator.

d. The prime mover may not return to its original speed. This depends upon the design of the speed control system. For speed control systems which are slow reacting, mechanical governors or electro-mechanical systems, this reduction of speed with increased load is desirable if the generator is operated in parallel with other generators (discussed later with parallel generator operations).

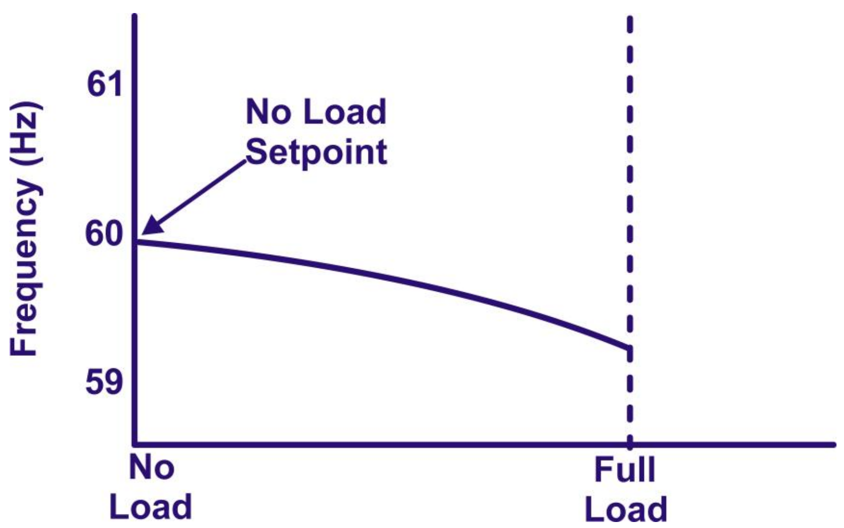
e. The speed control system needs an error signal (speed setpoint minus actual speed) to develop a control signal. If load is increased, prime mover output will match required power but will not return to its original speed. Therefore, speed (frequency) of the generator will be a little less. In other words, frequency output of an independent (not paralleled) AC generator will decrease as load increases. Picture-9 shows this effect on generator frequency with a variable load. The percent of frequency drop between no load and full load conditions is called speed droop and is calculated using the following equation:

$$\%\text{ speed droop} = \frac{S_{NL} - S_{FL}}{SNL} \times 100$$

SNL is no load speed

SFL is full load speed

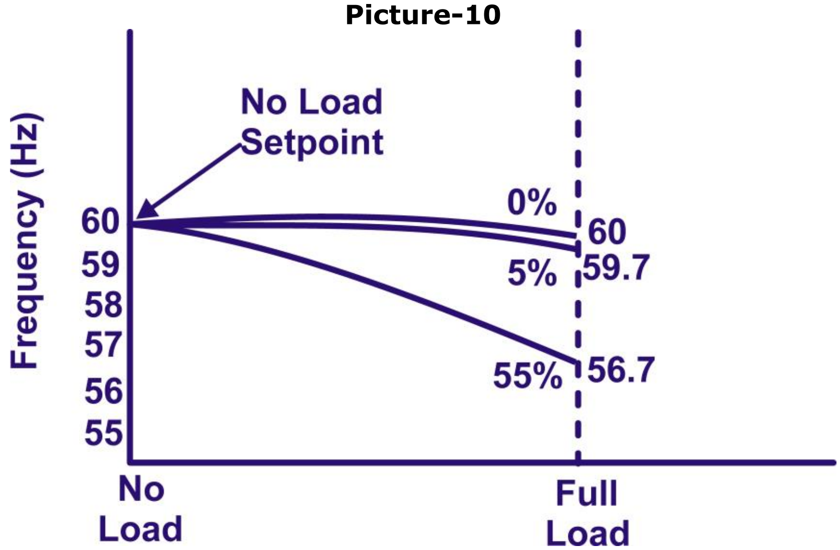
f. A governor with a 3 percent speed droop causes a 3 percent difference in speed and frequency between no-load and full-load values. Suppose a diesel generator with 5 percent speed droop is operating at its fully rated load and 60 hertz. When the load is removed, frequency will rise to 60 + 0.05 x 60 = 63 Hz. Picture-9 shows how the generator loses speed (and frequency) as load is added. The generating unit shown has a speed droop setting of 1.7% (60-59/60 = .017 or 1.7%). This type of speed control is commonly seen on emergency diesel generators at a BWR generating station.



Picture 9, Speed Droop of an Isolated Generator

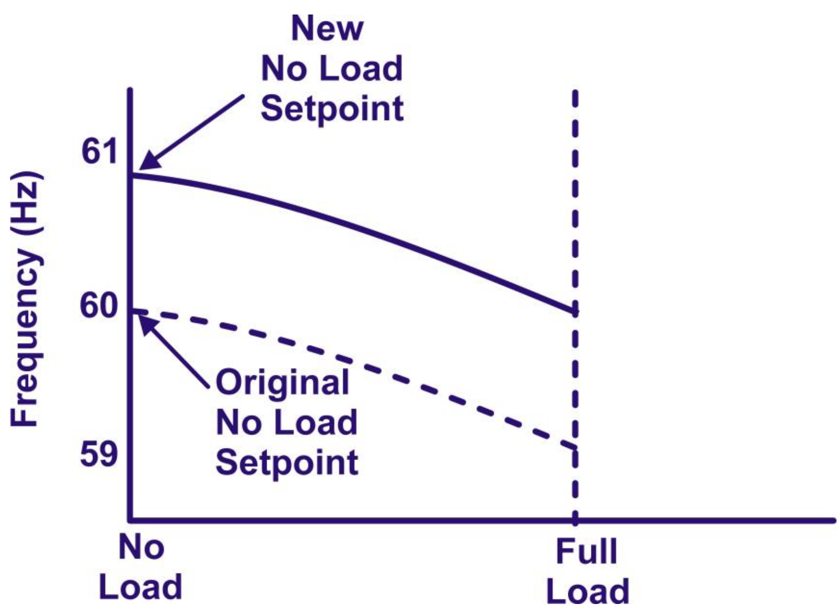
g. Some generators have prime movers whose droop characteristics can be changed. A common example of this is the emergency diesel generators at many BWR generating stations. Their governors can be adjusted from zero to some maximum droop. The adjustment, calibrated in percentage, is used to set the desired droop. One example is an emergency diesel generator with a maximum droop of 10 percent (speed decreases to 54 Hz at full load with the speed droop setpoint at maximum). When in standby, the setpoint is adjusted to 5. At this setpoint, the diesel generator frequency decrease is 0.3 Hz between no load and full load, speed droop of 0.5%. During surveillance testing, the setpoint is changed to 55. Now the frequency will decrease to 56.7 if it were fully loaded as the only source of power to an emergency bus (Picture-10).

Picture-10



Picture 10, Multiple Speed Droop Generator Load Curves

h. Turning the speed control to “raise” or “lower”, raises or lowers the no-load speed setting but does not change the droop. To compensate for “droop” in speed, a utility may decide to raise no-load speed set point to maintain 60 Hz for expected load. For example, if the generator whose droop characteristic shown in Picture-9, was a standby diesel generator which normally has full rated load applied when needed the operator could adjust no load setpoint up to 61 Hz. Therefore, when full load is applied, frequency of the generator output will be 60 Hz as shown in Picture-11.



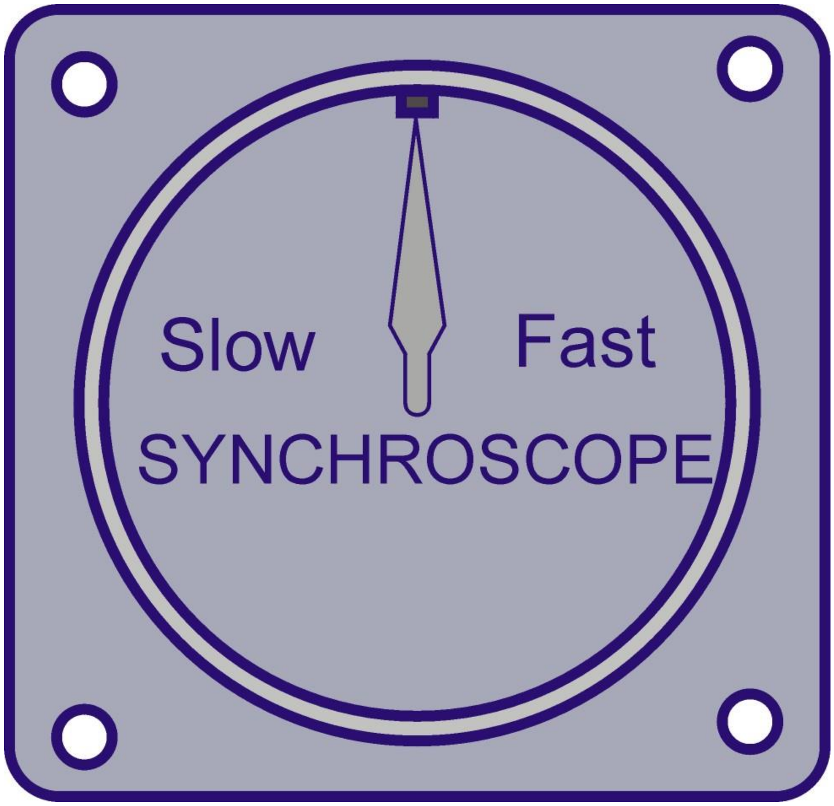
Picture 11, Compensating for Speed Droop

4. Synchroscope

   a. Several methods are used to ensure that a close match of frequency and phase voltage is obtained between the grid system and the in-coming generator. One of the most common methods is to use an instrument called a synchroscope.

   b. A synchroscope (Picture-12) indicates the voltage phase relationship between the incoming generator and the respected bus.

   c. If frequency of the incoming generator is lower than bus frequency, the synchroscope pointer will rotate in the direction marked “slow” (Picture-13A).



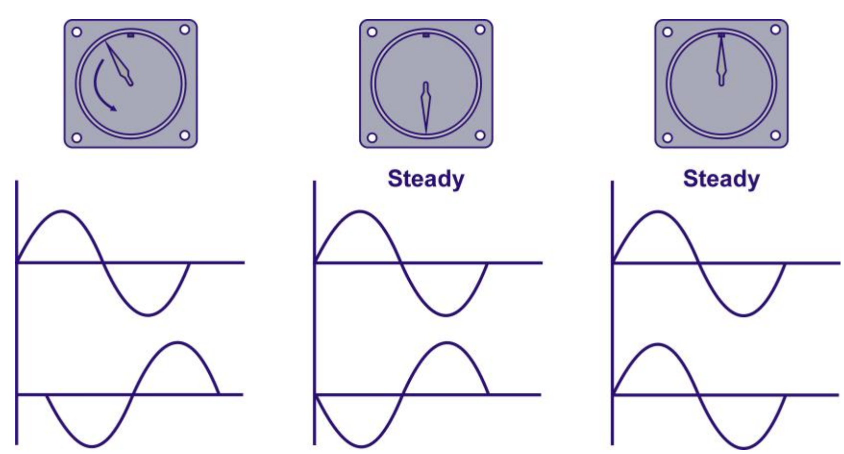
Picture 12, Synchroscope Dial

d. Any time the synchroscope pointer rotates, there is a frequency difference between the two points. If the pointer is rotating clockwise, the in-coming generator frequency is faster than the bus. If it is rotating counterclockwise, it is slower.

e. If the pointer stops at a position other than 0° (12 o'clock position Picture-13B), it is an indication that the incoming generator frequency is the same as the running bus but is out of phase by an error angle indicated. To correct this, the governor control (speed) of the incoming generator is increased. This will result in a slightly higher frequency and will cause the synchroscope pointer to revolve slowly in the "fast" direction.

f. Two frequencies can be different (pointer rotating) and still be in-phase (pointer passes through the 12 o'clock position). The pointer will rotate slower for a smaller frequency difference and remain in-phase longer. Generators should be paralleled as close to in-phase (0°) as possible to minimize mechanical and electrical shock to the system. When generators are being paralleled, the in-coming generator should be at a slightly higher frequency to ensure that it picks up real load and doesn't become motorized.

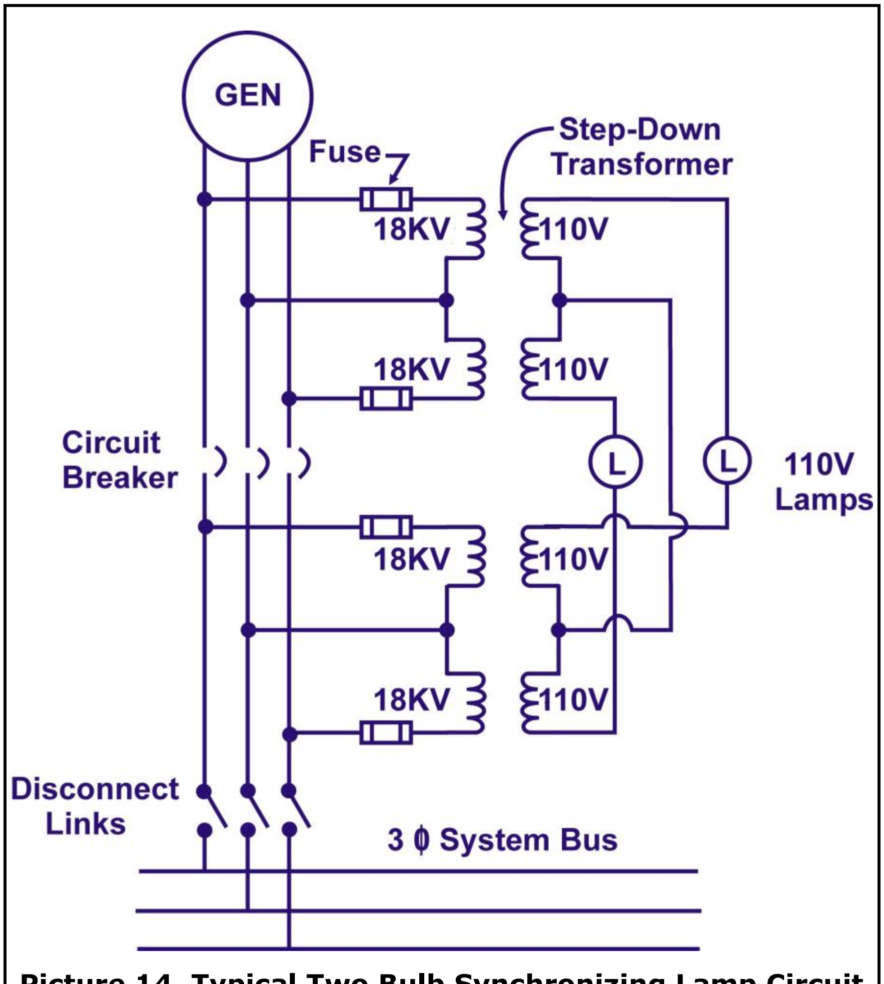
g. A more stable system will result. This means that during synchronizing operations the pointer rotates slowly in the "fast" direction. Ideally, generators should be paralleled in-phase and the breaker should close when the pointer is at the 12 o'clock position (0°). However, breakers are mechanical devices, which means a time lag exists between the time the switch is placed in "close" and the breaker actually closes. Consequently, it is a good practice to start the breaker-closing operation at about the 11-o'cock ("5 minutes till" position) of the synchroscope, to ensure the breaker actually closes near the 0E point. Once paralleled, the generator and bus will be locked phase with the synchroscope pointer stationary at 0° (Picture-13C).



Picture 13, Synchroscope Operation

5. Synchronizing Lamps

   a. Synchronizing lamps provide a means for checking the synchroscope operation, and could be used as a secondary method for determining the instant for paralleling if the synchroscope becomes defective. A typical two bulb synchronizing lamp circuit is shown in Picture-14.



Picture 14, Typical Two Bulb Synchronizing Lamp Circuit

   b. If the frequency of the incoming generator is different from that of the bus (usual for paralleling generator to a bus), both lamps will go alternately bright and dark in unison. When the lamps are dark, little or no current is flowing through the bulbs to make them light (no voltage difference, in phase relationship between the generator and the bus). When the lamps are dark, the synchroscope pointer should be at 0° and the two voltages in-phase. If the bulbs are not burned out, the lamps are always correct.

c. When lamps are used for synchronizing, the duration of the dark period should be timed and the breaker closed midway through the dark period. Timing is important, because the dark period may extend over 8° or more of error angle as current is too small to heat up the bulb filaments and make them glow.

6. Voltage

a. When synchronizing a generator with an energized bus, the proper amount of voltage must be present before closing the output breaker. This is known by comparing the in-coming, generator, voltmeter to the running bus voltmeter. In practice, generator voltage is adjusted by varying its field to bring voltage equal to, or just slightly greater than, that of the energized bus. This ensures that the generator does not become an inductive load, overloading other generators supplying the grid. Reactive power of parallel generators is controlled by the generators' fields.

7. Paralleling AC Sources

a. The procedure to accomplish this will vary depending upon the generator involved, the arrangement and components of the electrical distribution system, and the policies of the utility. The general steps for paralleling AC sources look something like this:

1) Ensure the breaker for the incoming machine is open.

2) Close electrical disconnects of the incoming machine.

3) Switch the voltage regulator to automatic.

4) Adjust the turbine or engine to proper rpm.
5) Using the speed governor-control switch, adjust frequency of the incoming machine so the synchronizing scope rotates slowly in the "fast" direction.
6) Adjust the automatic voltage regulator so that the voltage of the incoming machine is equal to or slightly higher than bus voltage.
7) Close the circuit breaker when the synchroscope is at the "5 minutes till" position.
8) Turn the synchroscope switch to off.
9) Turn the speed governor switch of the incoming generator to "raise" to pick up some load.
10) Increase generator load at the direction of the load dispatcher.

b. Reactive load should normally be distributed between parallel generators according to the bus condition and generators supplying the bus. This is accomplished by adjusting the automatic voltage regulator control for the affected generators as coordinated by the Load Dispatcher.

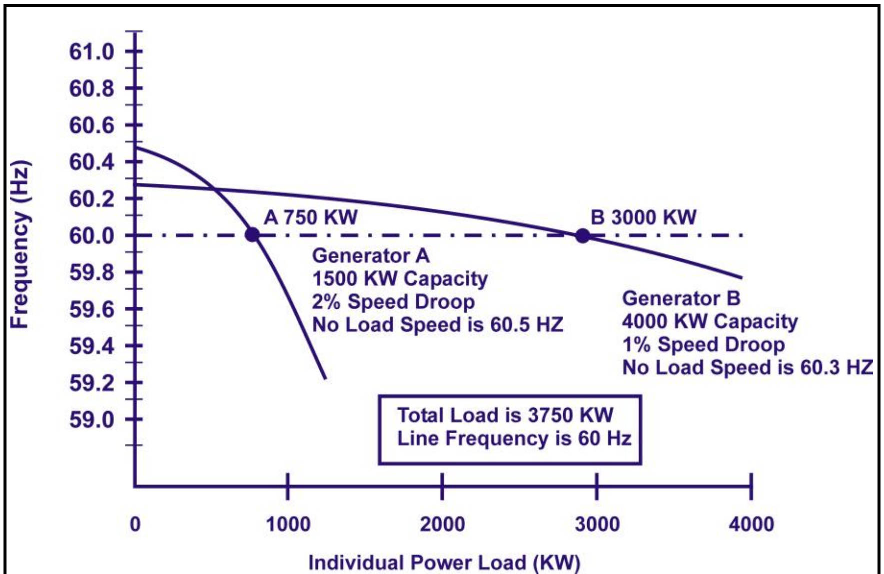
D. Parallel Generator Operation

1. Parallel Generator Speed Droop

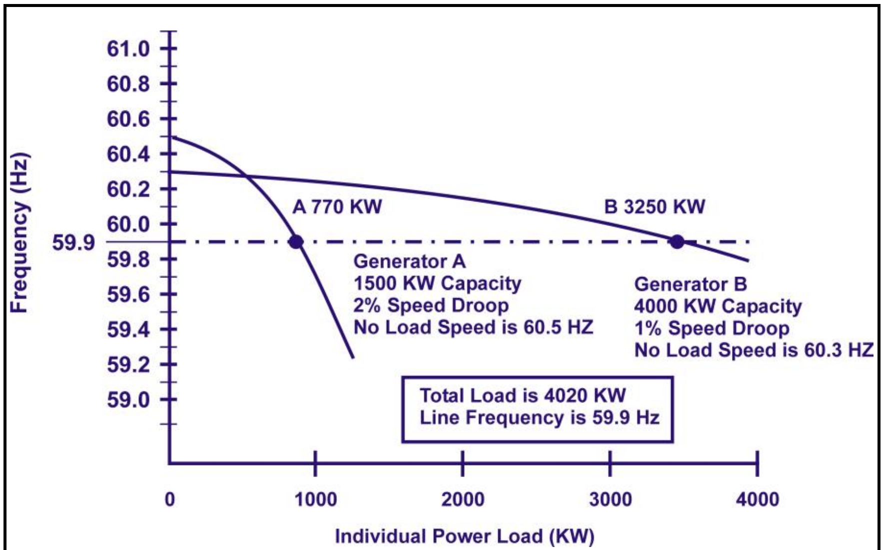
a. Speed droop was defined as the decrease in speed or frequency, of a machine from a no-load to full-load condition for an individual generator, not operating in parallel. For parallel generators, the existing grid frequency is the combined effect of the grid's generator outputs and true loads on the system. Amount of real load picked up by a generator is dependent upon its individual droop characteristics, no-load set point, and the frequency of the bus.

b. Picture-15a shows two different generators operating in parallel at 60 Hz and supplying a load of 3750 Kw. Due to the differences in droops, generator B has a larger share of total load (3000 Kw). Power is shared where the combined output of the generators equals demand. The output frequency changes until equilibrium is reached.

c. If more load is required than that generated, real power load on the generators will still increase to supply the demand. But, as Picture-15b illustrates, to supply additional true power (270 kw in this case), frequency of the system drops (59.9 Hz). Notice that generator curves have not changed and generator A picked up less of additional load than generator B due to different droop characteristics of the machines. This assumes that neither generating units no load setpoint (speed control adjustment) was changed.



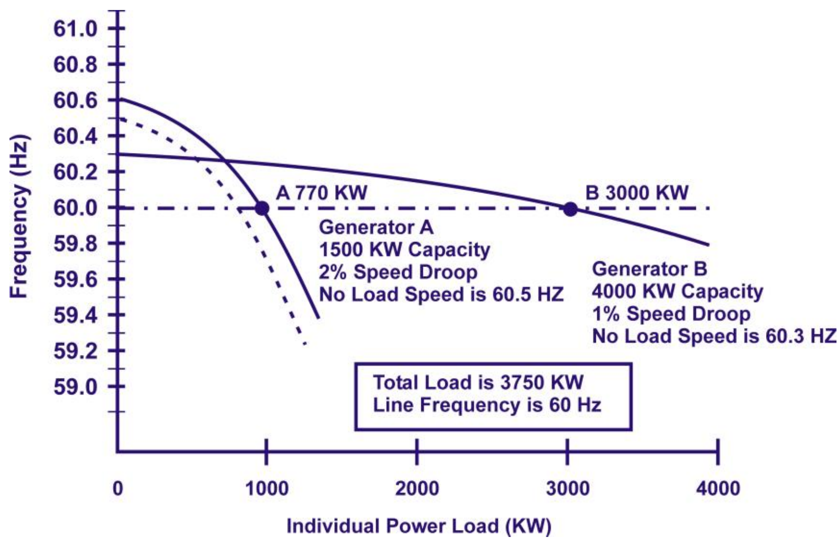
Picture 15a Parallel Load Sharing



Picture Increase in Real Load Without Load Following

d. To maintain system frequency, there must be an increase in energy supply. The prime movers must supply more power. For many generators, though not the main generator for a BWR, which is slaved to the reactor, this frequency decrease causes the prime mover to increase power.

e. To return frequency to 60 Hz (Picture-16) the no-load setpoint of generator A turbine is increased. This causes generator A to pick up more real load. When generator A assumes the additional load, frequency returns to its original value (60 Hz).



Picture 16, Effect of Increasing Power Input of a Generator's Prime Mover

f. The important points concerning real load sharing and speed droop are:

1) As power delivered by generator A's turbine increased, so did its share of true power. Line frequency also increased. For utilities with small total power capacities, a larger generator on the grid can significantly affect frequency if load demand is or generator output is changed.

2) Many utilities have large grid systems and numerous generators supplying many gigawatts (1 GW = 1000 MW). This means that the generating capacity of even the largest generator is small when compared to the total power of the grid. Therefore, for generating units supplying this type of grid, when the turbine speed control changes control valve position, the real load supplied will change (as observed by the meters), but changes in frequency will not be seen on control room instruments.

3) Therefore, it is commonly stated that changing the speed control switch on the prime mover results in change in real load only.

4) Because utility grids are tied together, for load changes to be seen in the control room, they must be very large and occur faster than the Load Dispatcher can coordinate the grid. This could occur if, by coincidence, many grid loads increase at the same time.

5) If grid load demand exceeds power generation, frequency decreases (rotor speed and power decreases) until a balance is obtained. This is not desirable since many components (e.g., clocks, electronic equipment) require 60 Hz to operate property. The alternate method of reducing power is to reduce voltage (brownouts). In severe cases, the utility may use blackouts, de-energize portion of the grid, to reduce load.

6) Emergency diesel generators at many BWR stations have a variable droop setting. The droop set point can be adjusted between zero and some higher value. These generators normally do not operate in parallel with the grid. When they are required for power generation, they supply a limited portion of the generating units internal loads. Therefore, droop settings are set equal at some nominal small value to limit frequency fluctuations with variances in load demand. However, when the generator (rated in kw) is paralleled to the grid (rated in GW) droop is set higher. This is usually seen during surveillances and is done to limit additional diesel generator load, should an increase in grid load occur.

7) This protects the diesel generator from overload. Load fluctuations (as much as 2 or 3 Mw) could occur almost instantly at any time.

2. Reactive Power Control

a. Suppose steam flow to the turbine is not changed and system demand is constant. Two voltages, incoming (generator's terminal voltage) and running (grid voltage) are rising and falling in perfect time with each other. By increasing the field voltage control on the generator, the field excitation amperes is increased. The two voltages still rise and fall in phase, always starting from zero and reaching a peak together. But now, the voltage generated inside stator coils (internal voltage) reaches a higher peak. To get there at the same time, it must rise faster and go higher than the generator terminal voltage which is the same grid voltage.

b. The action of this over-excited generator is just like a capacitor. If the generator is over-excited and acting as a capacitor, it will supply “magnetizing VARS” (positive, lagging VARS) to satisfy the grid's reactive load demand. The generator VARS are positive and supplying real load (positive watts).

c. Just the opposite effect occurs if the generator is under-excited (internal voltage less than terminal voltage). Instead of behaving as a capacitor, the under-excited generator behaves as an inductive_load, drawing magnetizing reactive power from the system to components for low field excitation. Reactive power is being supplied to the generator, therefore it must be negative. The VARS are negative but real power is still supplied to the grid. The under-excited generator is still supplying real power to the system but other generators in the system are supplying the under-excited generator's magnetic field.

d. Most large electrical power systems have much more inductive than capacitive loads and require “lagging” VARS to be generated along with watts of real power. Ideally all generators on the grid will be sharing the real and reactive load according to individual ratings. This prevents one generator from supplying too much current (real plus reactive) and overheating. The Load Dispatcher determines the required VARS.

e. In a properly balanced system, the only current flowing is that to real loads on the grid and that which circulates between load reactive fields and the generators. No current should circulate between the generators themselves. Any time current oscillates between two reactive components, it is called circulating current. In this case, circulating current is between the generator and loads on the grid. This is a requirement due to the design of large coils and transformers. However, under certain conditions circulating current can occur between generators themselves.

f. Suppose that generators on the grid are balanced so that reactive power output exactly matches reactive loads. If excitation of one generator is increased, the grid now has more reactive power than it needs. This causes grid voltage to increase. However, with many gigavars supplied to the grid for reactive load demands, this increase in voltage normally cannot be observed in the control room. Therefore, it is common to say that for a parallel generator the voltage control switch changes VARS, not voltage. This excess reactive power is expended between generators on the grid. The excess reactive current circulates between the generators and is dissipated as reactive losses (I^2X) in stator windings. Excessive circulating current should be minimized because it causes inefficient operation and unnecessary heating of the generators. It is the Load Dispatcher's responsibility to maintain power grid voltage by balancing reactive power generation and reactive power load demand.

g. The power factor of an AC distribution system (e.g., the grid) is dependent upon the loads of that system. A generator operating singly, then, operates at the power factor of the load supplied. When two or more generators operate in parallel, the power factor at which each operates is determined by its individual field excitation, but the vector sum of the generator's outputs will yield the system's power factor. Since most loads are inductive, the load power factor will be some lagging power factor.

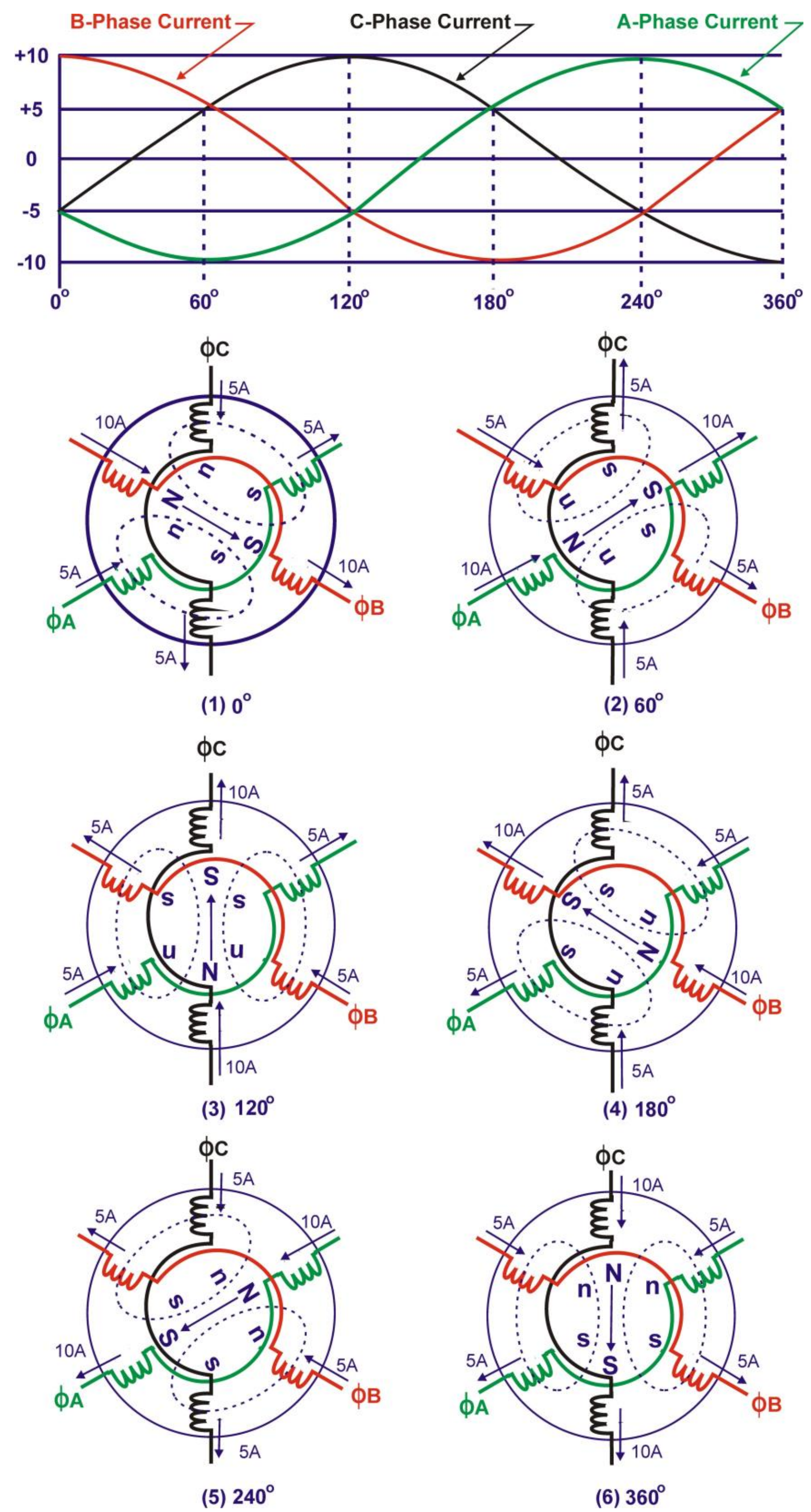
E. AC MOTORS

1. Advantages

   a. Most of today's power generating systems produce alternating current. Therefore, a majority of motors used in commercial industry are designed to operate on alternating current. However, there are other advantages to AC motors besides wide availability of AC power. In general, AC motors are less expensive and do not employ commutators. This eliminates the problem of dangerous sparking and frequent brush replacement. Slip rings will not wear down brushes at the rate a commutator does. AC motors are manufactured in many different sizes, shapes, and ratings for use on an even greater number of jobs. They are designed for use with either three-phase or single-phase power systems. The rest of this chapter will deal with the operating principles of two common types of motors: the rotating-field induction motor and the synchronous motor.

2. Development of a Rotating Field

   a. Stator phase windings are symmetrically placed on the stator. The rotating field is set up by out-of-phase currents in these field windings. Picture-17 illustrates a rotating field produced by stationary coils, or windings, supplied by a three-phase current source. The principles are the same for a single-phase motor but only one north and one south pole will rotate. Field rotation will be observed in the figure by "stopping" it at six selected positions, or instants. These instants are marked off at 60 degree intervals on the sine waves which represent currents in the three phases (A, B, and C).



Picture 17, Development of a Rotating Field

b. For the purpose of this explanation, positive current flows out at the motor phase table. At instant 1, the current in phase B is maximum positive. (Assume positive 10 amperes and current in phases A and C is at half negative value (minus 5 amperes). The resulting field at instant 1 is established downward and to the right (arrow NS). The major portion of this field is produced by the B phase (maximum current) and is aided by the adjacent phases A and C (half strength).

c. The weaker portions of the field are indicated by the letters “n” and “s”. Because the fields effectively combine to form one field of a given direction and strength, this is a two-pole field (one north and one south pole). This two-pole field extends across the space that would normally contain the rotor.

d. At instant 2 current in phase B is reduced to half positive value (plus 5 amps). Current in phase C has reversed direction and is plus 5 amps, and current in phase A has increased to minus 10 amps. The resulting field at instant 2 is now established upward and to the right (arrow NS). The major portion of the field is produced by phase A (full strength) and the weaker portions by phases B and C (half strength). Thus the magnetic field has rotated counterclockwise. This process continues at a speed determined by the applied frequency (60 Hz for grid loads). Development of a rotating field in a single-phase motor is the same except only full strength poles (N, S) and not the four half strength poles (2n, 2s) are developed.

e. The direction of rotation of the magnetic field of a three-phase motor may be changed by interchanging any two line leads to the three motor terminals. Most induction motors used by industry are three-phase due to their efficiency.

3. Starting Current

a. The relationship of starting current and rotor counter emf in an AC motor is basically the same as for DC motors with one additional factor, inductive reactance involved.

b. When an AC motor is first started, no current is flowing in the rotor to produce cemf. Therefore, the only restriction to current is the resistance and inductive reactance of the motor. Since inductive reactance is relatively constant (inductance, L, does not change after manufacturing and frequency is relatively constant) it can be assumed that total opposition to current flow (prior to rotor rotation) is still small even though X_L is about ten times as great as R. Whereas starting current for a DC motor without starting resistors is approximately 100 times its average running current, an AC motor not only has its stator resistance to limit starting current but also inductive reactance. An AC motor's impedance (Z) is approximately ten times that of a DC motor. Starting current for an AC motor is approximately one tenth that of a DC motor. Starting current of an AC motor is approximately 5 to 7 times its normal running current (point A, Picture). The equation for current flowing through an AC stator is similar to that of a DC motor with the exception of total impedance.

$$I_s = \frac{E_s - E_c}{Z_s}$$

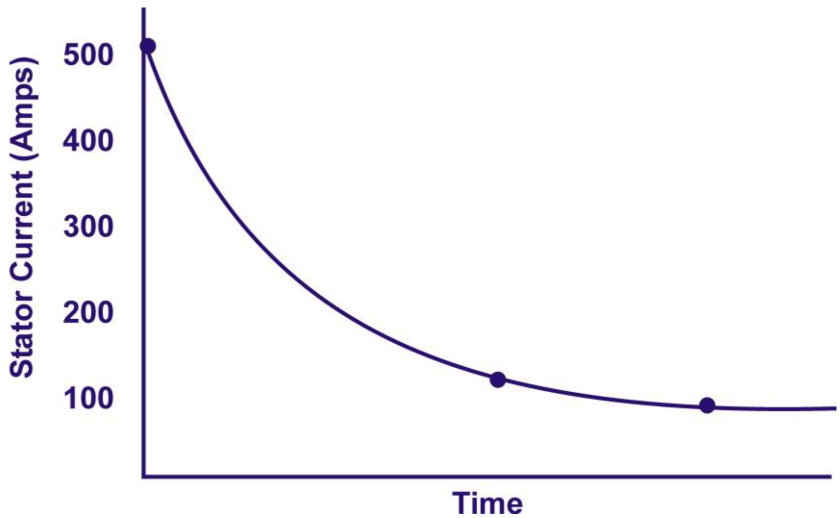
Where:

I_S is the current flowing through the stator

E_S is the applied voltage across the stator

E_C is the counter emf

Z_S is the total impedance of the stator



Picture 18, AC Motor Starting Current Curve

c. As rotor speed increases, counter electromotive force increases, lowering stator current between points A and B (Picture-18). Starting current continues to decrease until the rotor reaches its running speed for shaft load. Current drawn at this time is called running current (point C, Picture-18).

d. If this motor start were observed on an ammeter, current would initially spike to approximately seven times normal running current. As motor speed increases, the current indicated would decay to its normal running current.

4. No Load Starting

a. When an AC motor is unloaded, the required torque for starting will be minimum, just enough to overcome friction and rotor windage losses. Therefore, required stator current is much less than the rotor were loaded. To limit starting current, most motors are started with no load.

The rotor will increase to rated speed in a shorter time. This limits the heat (I^2R losses) in the stator.

F. In SUMMARY

1. The principles of operation for an AC generator are similar to that for a DC generator. Laws that govern generator and motor action are the same. Unlike a DC generator, the AC generator uses slip rings. Most large commercial generators use the rotating field design due to limited power capabilities of rotor brushes.
2. Three-phase power delivers a higher average power more efficiently than a single-phase source. This is why most large loads, such as large industrial motors, are designed as three phase loads.
3. By changing the field excitation of an independently operating AC generator, voltage output will change accordingly. If more power is delivered to the generator by its prime mover (e.g., opening the control valves of a turbine) frequency output of the generator will increase. The opposite occurs if less power is delivered by the prime mover. As the load on an independently operating AC generator is changed, its speed will change. Difference in speed between no-load and full load conditions (in percent) is called speed droop.
4. When a generator is paralleled with other generators, the incoming generator should be at a slightly faster speed than the others. This ensures the generator does not become a load (motorized) but actually picks up some of the real load on the grid or bus. When synchronizing a generator, the synchroscope should be rotating slowly in the fast direction prior to paralleling. It is very important to minimize the spike caused by paralleling a generator not exactly in phase with the energized system. To ensure the breaker closes when the generator is in-phase, the breaker control switch is placed in the “close” position when the synchroscope pointer passes the 11

o'clock position. Due to delay caused by the mechanical breaker, the breaker will close at a point very close to the 12 o'clock position on the synchroscope (in phase). Output voltage of the incoming generator should be equal to or slightly above the system voltage. This ensures that the incoming generator picks up some of reactive load and doesn't become an inductive load itself.

5. Once an AC generator is operating in parallel with one or more generators, the effect of speed control of its prime mover and voltage control of its field will not be the same as when the generator was operating independently. If more power is supplied by the generator's prime mover, the generator will produce more real power (watts). If additional real power is consumed by additional real power loads on the system, no further effects are seen. However, if excess real power is delivered to the system, frequency of the system will increase. If the excess real power is relatively small (e.g., 50 megawatts on a 500,000 megawatt grid) then the increase in system frequency will be unnoticeable in the control room. As the excitation field strength is increased in a paralleled AC generator, more reactive power is produced by the generator. If additional reactive power is used by reactive loads, no further effect will be seen. However, if excess reactive power is supplied, circulating currents will develop between generators. If the excess reactive power is insignificant when compared to total reactive power consumed, the increase in system voltage will not be seen in the control room. Circulating currents that occur between generators due to these conditions will limit efficiency and may cause overheating. Normally reactive load is divided between generators according to individual rating and grid demand. This prevents over burdening any generator.

6. Principles behind motor action and counter electromotive force generation are the same for AC motors as DC motors. However, they occur a little differently. An AC induction motor uses the rotating field of the stator to

induce current in the rotor. The motor then has a current-carrying conductor in a magnetic field (the two requirements for motor action). Therefore, the rotor starts to turn and accelerates to near the speed of the rotating field. As long as there is relative motion between the rotor and the rotating field of the stator, current will be induced in the rotor. Therefore, an induction motor will never rotate at the same speed (synchronous speed) as the stator field. The difference between synchronous speed and the actual rotor speed is slip.

7. Basic principles behind starting current in an AC motor are essentially the same as a DC motor. However, because a stator provides inductive reactance to an AC current, inductive reactance must be included with winding resistance when starting currents are discussed. Inductive reactance is about 10 times as large as winding resistance. Therefore, when an AC motor is first started, and no counter electromotive force produced, current will spike approximately 10 times higher than normal operating current. This is less than the 100 times normal value for DC motors. As speed of the motor increases, more counter electromotive force is induced into the stator, and starting current will decay until current levels to that required to maintain speed for the present load.

PRACTICE:

1 What is transformation?

2. What is the basic difference between AC motors/generators and DC motors/generators?