CATERPILLAR®

GENERATOR SETS

ELECTRICAL FUNDAMENTALS

CATERPILLAR ENGINE DIVISION

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I. INTRODUCTION

The continuing growth of civilization and its technology has been accompanied by an ever-increasing dependence on electrical power. Business and industry as it exists today cannot function without a reliable supply of electricity. In the case of hospitals, broadcasting stations and other facilities providing essential public services, a constant supply of electrical power may spell the difference between life and death. Most often the need for electrical power is met by public utility companies with their central generating plants and vast power distribution networks. Such systems, however, are subject to occasional malfunctions, which can have serious effects unless the user is prepared to supply emergency power from onsite sources. In addition, many users are finding that with the improved energy recovery techniques now available it is advantageous from the standpoints of economy and reliability to supply all of their power requirements with on-site equipment. In remote areas, where centrally-generated power, if available at all, is expensive and less than optimally reliable, the advantages of generator set power are even more obvious. Diesel and natural gas generator sets have proven their effectiveness in meeting needs for both prime and standby power systems.

It is important that persons involved in the application of generator sets have an understanding of the fundamentals of electrical power generation and distribution. This manual is intended to provide the information necessary to correctly apply the guidelines found in the Generator Set Application and Installation Guide and the requirements listed in consulting engineers specifications. Readers who have had little contact with the power generation and distribution field will find this book a reliable aid to learning. The more experienced can use it as a review or reference. Tables, Formulae and Technical Terms will be useful to all who work in this field.

II. FUNDAMENTALS OF ELECTRICITY

Electricity is used by millions of people daily, but understood by only a relative few. Fortunately, no extensive knowledge is needed to put electricity to work. A vast array of electrical devices may be connected and operated by following a few simple rules and safety measures. All of the complicated planning and design work has been done by engineers specializing in this field. However, when one becomes involved in the design of electrical systems, a fairly complete knowledge of fundamentals becomes necessary.

The proper application of generator sets demands some general awareness of the nature of electricity, the means by which it is generated and the ways in which it may be applied to perform useful work. The material presented in this chapter is intended to aid readers whose experience in this area is limited.

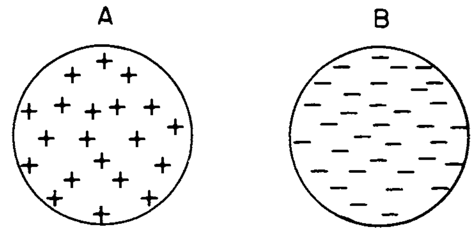
ELECTRICAL CHARGES AND THEIR MOVEMENT

The phenomenon called "electricity" is based upon the existence and movement of charged particles. All material objects are made up of tiny particles called molecules which, in turn, are composed of combinations of atoms of the various chemical elements. Atoms consist primarily of even smaller particles called neutrons, protons and electrons. Neutrons are, as the name implies, neutral particles; that is, they carry no charge. Protons and electrons, on the other hand, are charged particles. Each has an electric field of force surrounding it in much the same way as the earth is surrounded by its gravitational field of force. Protons and electrons carry positive and negative charges, respectively. It is characteristic of these charges and their respective fields that like charges repel and opposite charges attract each other. Thus, two electrons in close proximity will exert a repellant force on each other.

In most atoms the charges are equally balanced. For every positively charged proton there is a negatively charged electron. The protons and neutrons make up the nucleus of the atom—the very dense central portion—while electrons travel around the nucleus in orbital paths. Because the electrons are not confined to the tight nuclear structure it is possible for them to be torn away from the atom when external forces are applied. If one or more electrons are removed from an atom, the charges are no longer balanced, and the atom is left with a net positive charge. Such an atom is called an ion. The electron which has been removed is a "free" electron.

Electrical Potential

By certain techniques, it is possible to remove some of the electrons from a body of material and transfer them to another body. The body from which the electrons are taken then has more positive particles than negative and is positively charged. The body of which the electrons are transfered has more negative charges than positive and is therefore negatively charged. Figure 1 shows two spheres which have been charged in this manner. Of course each sphere still has a large number of both positive and negative charges, but for clarity only the excess charges are shown.



Two Charged Spheres
Figure 1

Charged particles always tend to distribute themselves evenly over the volume of material in which they reside (assuming that no external forces are applied), much as air molecules distribute themselves evenly throughout a room. If a path were available between the two spheres along which electrons could move, those in sphere B would move along the path onto sphere A until they were evenly distributed between the two spheres and a balance of charges was restored. The excess electrons in sphere B thus have a potential energy with respect to sphere A, just as a stone suspended above the surface of the earth has a potential energy because of the gravitational force acting upon it. The stone will exert a force upon the device used to suspend it. The electrical equivalent of this force is **potential difference** or **electromotive force** (EMF). The unit by which this force is measured is the **volt,** abbreviated (V). In electrical formulae the letter (E) is commonly used to denote this force. Potential difference is often referred to simply as **voltage.**

If the stone mentioned above is released, it will fall to the earth, thereby changing its potential energy into other forms of energy, such as momentum while it is falling, and sound and heat upon impact. Similarly, the potential energy of electrons may be converted to other forms of energy when the electrons move, and these forms of energy may be very useful. Every lightning storm is a graphic demonstration of this principle. The movement of electrons through the air from the negatively charged earth to a positively charged cloud overhead generates a tremendous amount of light, sound and heat as the moving electrons release some of their potential energy to break down the molecular structure of the air.

Current

The movement of a number of electrons is referred to as an electrical **current,** by analogy with the flow of water in a stream or river. The basis unit of electrical current is the **ampere**, often shortened to "amp" and abbreviated (A). In electrical equations, current is usually represented by the letter (I). The ampere is a measure of the number of electrons passing a given point per unit time. Although current flow is actually composed of moving electrons, conventional electrical theory treats current as if it were the movement of positive charges. This convention was adopted before the mechanics of electricity were fully understood. Throughout the present text, the conventional direction of flow will be used.

Conductors and Insulators

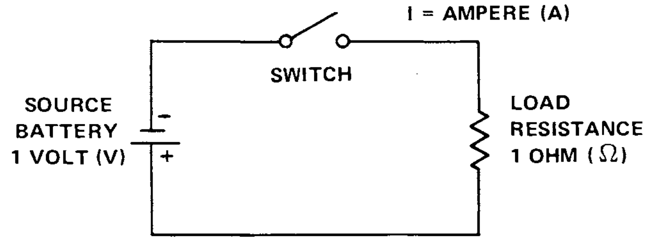
Electrons move only with great difficulty through many substances such as air, glass or rubber. A large potential difference (voltage) is required to force charges to move even a short distance through such mediums. These substances are called **insulators** because they effectively block the movement of electrons. Through other materials, such as most metals, electrons can move with comparative ease. These materials are termed **conductors** because they "conduct" the flow of electrons. Materials whose conductive properties fall in between conductors and insulators are known as **semiconductors**. These substances have found important applications in the fabrication of modern diodes and transistors, devices used to control the flow of electrical current. Insulators, it should be noted, offer a great amount of opposition to the flow of current until an excessively large voltage is applied, at which point they "break down" and allow the current to flow more readily. The voltage required to cause this change in a substance is known as **breakdown voltage.** It depends not only on the type of material but also on the thickness, which determines the path length which the electrons must traverse.

Resistance

Resistance is the term used to denote the amount of opposition which a substance offers to the flow of electrical current. The basic unit of resistance is the **ohm,** denoted by the Greek symbol Ω . The amount of resistance that a given object exhibits depends not only on the type of material from which it is made, but also on its physical dimensions, such as cross - sectional area and length. For a given physical configuration, objects made from insulating materials have high resistance while those made from conductive materials have relatively low resistances.

Electrical Circuits

An electrical **circuit** is a closed path through which electrons can flow from a source of potential difference, or voltage, through a **load,** a device in which electrical energy is used, and back again to the source. In the circuit shown in Figure 2, the source is a battery having a potential difference at its terminals of 1 volt. The load is a **resistor,** a circuit element having a specified resistance, in this case, 1 ohm. The source is connected to the load by means of conductors, drawn as lines, whose resistance is small enough that it may be ignored for the present. The circuit also includes a **switch,** a device for interrupting the flow of current. When the switch is open, as shown, the circuit is broken and current cannot flow. When it is closed the contacts touch, the circuit is completed and current flows through the load.



Simple Electrical Circuit
Figure 2

Ohm's Law

A fundamental law of electricity, **Ohm's Law,** relates the quantities of voltage and current in a circuit. It states that the voltage which appears between the terminals of a resistance is equal to the value of the resistance in ohms multiplied by the magnitude of the current flow in amperes. In mathematical terms, this law is written:

$$E = IR \qquad \textbf{(Eq. 1)}$$

where E = voltage in volts
I = current in amperes
R = resistance in ohms

By simple algebra this equation may be written:

$$I = \frac{E}{R} \qquad \textbf{(Eq. 2)}$$

or

$$R = \frac{E}{I} \qquad \textbf{(Eq. 3)}$$

If two of the three quantities are known, the third may be found by using the appropriate equation. In the circuit of Figure 2, the voltage and resistance are given. The current which will flow can be found from Equation 2:

$$I = \frac{E}{R} = \frac{1 \text{ volt}}{1 \text{ ohm}} = 1 \text{ ampere}$$

Series Circuits

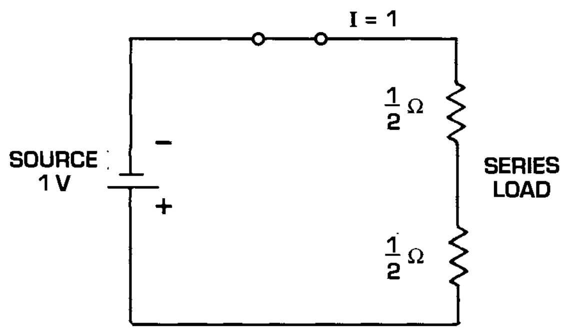
Figure 3 shows a somewhat more complicated circuit. Here the load is composed of two resistors connected in **series.** All of the current flowing in the curcuit must flow through both of the resistors before it can return to its source. The total resistance of the load is the sum of the resistances of the two resistors. Since each resistor has a value of 1/2 ohm, the total load resistance is one ohm, as in the former circuit and the total current remains the same. The total resistance, R_T, of any number of resistors In series is given by:

$$R_T = R_1 + R_2 + R_3 + \ldots R_N \qquad \text{(Eq. 4)}$$

The voltage at the terminals of one of the two resistors may be found from Equation 1:

$$E = IR = 1 \text{ ampere} \times 1/2 \text{ ohm} = 1/2 \text{ volt}$$

Because the two resistances are equal, the voltage applied to the two in series divides equally between them.

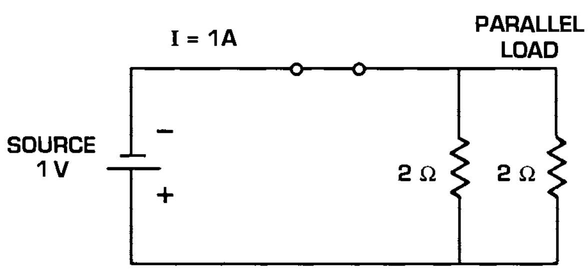


Circuit With Series-Connected Load
Figure 3

Parallel Circuits

The load shown in the circuit of Figure 4 is somewhat different. Here the resistors have been connected side-by-side instead of end-to-end. When this configuration is used, the resistors are connected in parallel. In this case there are two paths for the current to follow and it consequently divides, part passing through one resistor and part through the other. The total resistance of any number of resistors connected in parallel is given by the equation:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots \frac{1}{R_N}} \qquad \text{(Eq. 5)}$$



Circuit With Parallel-Connected Load
Figure 4

The effective resistance (R_T) of the resistors composing the load in Figure 4 is:

$$R_T = \frac{1}{\frac{1}{2} + \frac{1}{2}} = 1 \text{ ohm}$$

The total current flowing in the circuit is therefore once again one ampere. However, because the terminals of each resistor are effectively connected across the terminals of the battery, the voltage across each resistor is one volt. The current flowing through each resistor may be found from Equation 2:

$$I = \frac{E}{R} = \frac{1 \text{ volt}}{2 \text{ ohms}} = 1/2 \text{ ampere}$$

In this circuit, the current will divide equally between the two resistors. If the resistances were different, however, the current through each resistor would be different.

Parallel circuits are used in every household electrical power system. Appliances are connected in parallel across the source of incoming power. Electrical appliances are designed to operate on a specified voltage, but they draw varying amounts of current, since the internal resistance of each type of appliance is different. By connecting the devices in parallel, the voltage at the terminals of each one will remain constant, even though the current flow through them may be different.

Power

If the circuits shown in any of the above figures were actually connected, the resistors would become warm. The potential energy of the electrons is changed to heat energy as they pass through the resistances. The heat (or other forms of energy) produced is the **power** which the load dissipates. It is a function of the applied voltage and the amount of current flowing through the load. The unit of quantity for electrical power is the **watt**, abbreviated (W) and denoted in electrical formulae by the letter (P). The law relating power to the other quantities in an electrical circuit is given by the expression:

$$P = IE \qquad \text{(Eq. 6)}$$

where P = power in watts
I = current in amperes
E = voltage in volts

This equation for power may also be transposed to:

$$I = \frac{P}{E} \qquad \text{(Eq. 7)}$$

or

$$E = \frac{P}{I} \qquad \text{(Eq. 8)}$$

From Ohm's law it is known that $E = IR$. If this expression for voltage is substituted in the power law, we can derive the additional equation:

$$P = I^2R \qquad \textbf{(Eq. 9)}$$

If we use the equation for current from Ohm's law, $I = \frac{E}{R}$, the equation for power becomes:

$$P = \frac{E^2}{R} \qquad \textbf{(Eq. 10)}$$

As an example of the way in which these equations may be applied, consider again the circuit in Figure 2. The power dissipated by the one-ohm load may be found by using Equation 10:

$$P = \frac{E^2}{R} = \frac{(1\ \text{volt})^2}{1\ \text{ohm}} = 1\ \text{watt}$$

Or, since the current flowing in the circuit has already been calculated to be one ampere, Equation 6 could be used:

$$P = IE = 1\ \text{ampere} \times 1\ \text{volt} = 1\ \text{watt}$$

It should be observed that the power consumed in the load and given off in the form of heat is the same amount of power being supplied by the battery. Since the load is dissipating one watt of power, the battery must be releasing one watt of power. The watt, then, can be a measurement of either the power supplied or the power consumed in a given circuit.

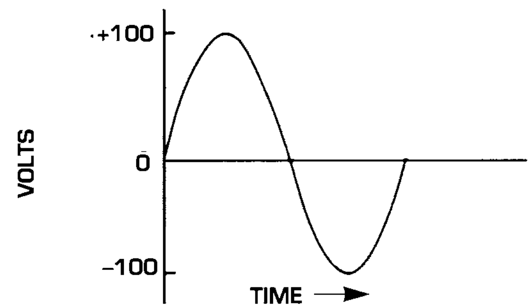
The form of power released at the load in an electrical circuit is dependent on the type of device used as a load. If a light bulb, for example, is connected in place of the resistor in Figure 2, the electrical energy is converted to light and heat. If an electric motor is substituted, the energy is changed to mechanical motion and heat.

Energy

Power is the rate at which energy is produced or consumed. The total energy expended in an electrical circuit is expressed as the product of the instantaneous power consumption and the number of hours that power is expended. The unit of quantity for energy is therefore the **watt-hour**. (A different unit, the ampere-hour, is generally used to specify battery energy-storage capability for reasons which will be discussed later.) The watt-hour is commonly employed by utility companies in measuring the amount of electrical energy used by their customers. While the watt is a measure of the rate of energy consumption, the watt-hour is the measure of the total quantity of energy consumed.

ALTERNATING CURRENT

In the circuits discussed above, the current flow has always been in the same direction, dictated by the polarity of the source. Current flow which always moves in only one direction in a given circuit is referred to as direct current (DC). All circuits using batteries as energy sources operate on direct current because the polarity of batteries does not change.



Alternating Current Waveform
Figure 5

Another mode of current flow is much more common in the generation and distribution of electrical power. In this form, the polarity of the energy source reverses periodically, causing the direction of current flow in the load to reverse also. Current flowing in this manner is known as **alternating current** (AC). Figure 5 is a graph of the magnitude and polarity of the output voltage of an alternating current generator. The voltage starts at zero, rises to a certain positive value, drops back to zero, continues to increase in the negative direction until it reaches a maximum, and again falls to zero. This process is repeated continuously as long as the generator is in operation. One complete excursion, from zero to a positive maximum, through zero to a negative maximum and back to zero is known as one **cycle**. The graphical representation of a voltage plotted against time is the **waveform** of that voltage. The waveform shown is a **sine wave** because it corresponds to the sinusoidal form obtained by plotting the value of the trigonometric sine function for increasing angles. It is also "symmetrical" about the zero axis.

Frequency

The **frequency** of an alternating current or voltage is the number of cycles completed within a one-second period. The unit of frequency is the **hertz**, abbreviated (Hz); one hertz is one cycle per second. One of two "standard" frequencies is supplied by the commercial (utility) power sources in various parts of the world. In much of North America, 60 Hz is the standard frequency. Europe is generally 50 Hz. Countries in South America, Africa, Asia, and the Pacific Basin have 50 Hz as standard. Some of these areas have standardized on 60 Hz. Some countries have two frequencies and others are changing from

50 Hz to 60 Hz. A very limited number of mines and processing plants have their own 40 Hz, 25 Hz, or DC power plants. It may be seen that the reversal of polarity occurs rapidly, with typically 1/60th or 1/50th of a second required to complete an entire cycle.

AC Voltage and Current

The measurement of voltage in AC systems is somewhat more complex than with direct current, since the magnitude is a function of time. One method of treating the problem is to measure the voltage at the maximum points of the waveform. The value obtained is known as the **peak voltage**. In Figure 5, the peak voltage is 100 volts. If the measurement is made from the maximum value of one polarity to the maximum of the opposite polarity, the **peak-to-peak** voltage is obtained. In Figure 5, the peak-to-peak voltage is 200 volts.

A more useful, hence more widely accepted measure of AC voltage or current is the RMS (root means square) value. RMS voltage is usually specified in the requirements of electrical devices. A requirement for a 240 volt generator almost universally refers to the RMS voltage. A circuit breaker having an interrupting capacity of 10,000 amperes refers to RMS amperes unless other designations are quoted, such as peak. If voltage waveform is a sine wave, the RMS voltage relates to the peak value as follows:

$$\text{RMS voltage} = 0.707 \times \text{peak voltage} \quad \textbf{(Eq. 11)}$$

or

$$\text{Peak voltage} = 1.414 \times \text{RMS voltage} \quad \textbf{(Eq. 12)}$$

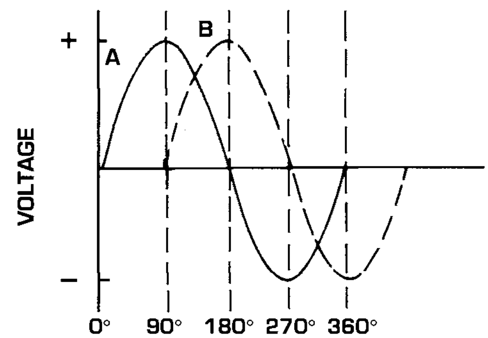
A 120 volt (RMS) voltage has a peak value of 169.7 volts.

Equations 11 and 12 also apply to current. The peak current is 1.414 x RMS current. Thus, a 10 ampere (RMS) heater passes 14.1 peak amperes at the peak of the AC voltage wave.

"Effective" values of AC voltage or current relate to the heating capacity of the AC voltage when applied to a given resistance. A pure DC voltage is then applied to that resistance and increased in value until the heating effect equals that of the AC voltage. The value of that DC voltage defines the "effective" value of the AC voltage. If the wave form is a sine wave, the effective value will equal the RMS value. This one relation causes the two terms to be used interchangeably. Later references avoid mention of the terms "effective voltage" or "effective current."

Phase

Another factor of importance when dealing with AC waveforms is **phase**, the relationship in time between two waveforms of the same frequency. Suppose that two AC generators are operating simultaneously. If their output voltages both start at zero at precisely the same time and if they are both of exactly the same frequency, then the times at which they reach their positive maximums, their negative maximums and their zero voltage points will be identical. In this case the two voltage waveforms are in phase. If, however, the waveforms start at different times or if they are of different frequencies, they are said to be out of phase. Corresponding points on the waveforms no longer coincide in time.



Two AC Waveforms 90 Degrees Out of Phase
Figure 6

Figure 6 shows, superimposed on the same drawing, two waveforms which are slightly out of phase. Wave A is said to **lead** wave B (which in turn **lags** wave A) since it apparently started earlier in time. For the sake of measuring phase differences, the time required to complete a full cycle of a sine wave is divided into 360 electrical degrees. The amount by which wave B lags wave A in Figure 6 may be measured as 90 degrees.

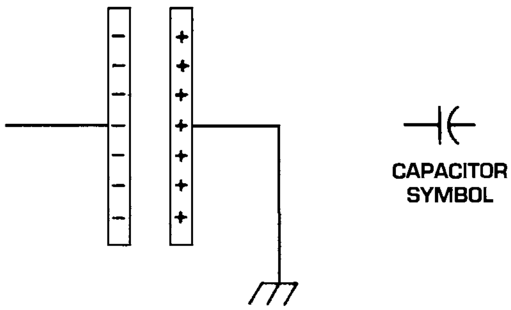
Reactance

In instances where the load applied to an AC generator is a resistance, the voltage and current in the load circuit are in phase. When the voltage is zero the current is zero; when the voltage reaches its positive maximum, the current is also maximum in the positive direction, etc. If a **reactance** is introduced into the circuit, however, the current waveform may actually lead or lag the voltage waveform. Reactances are of two types: capacitive and inductive. Capacitive reactance will be considered first.

Capacitance

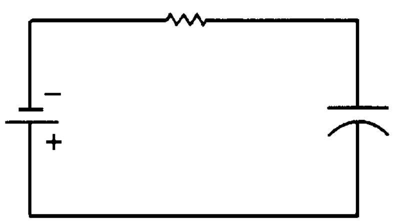
If two plates of metal are placed in close proximity to each other as shown in Figure 7, and a negative charge is applied to one of the plates, negative charges at the adjacent surface of the other plate will be repelled. If negative charges on this second plate are allowed to drain off to some large reservoir of charges, such as the earth, the two plates will maintain a charged condition. The plates have then stored electrical energy. A device of this type is known as a **capacitor** and is usually represented in electrical drawings by the symbol shown at the right in the drawing. The amount of energy which can be stored in a capacitor at a given voltage is dependent on the size of the plates and the spacing between them, as well as the material which separates them.

The storage capability is known as the **capacitance** of the device and is measured by a unit called the farad. Capacitors have only a small fraction of the energy-storage capability which batteries exhibit, but they can accept and release their charges very quickly because no chemical reactions are involved.



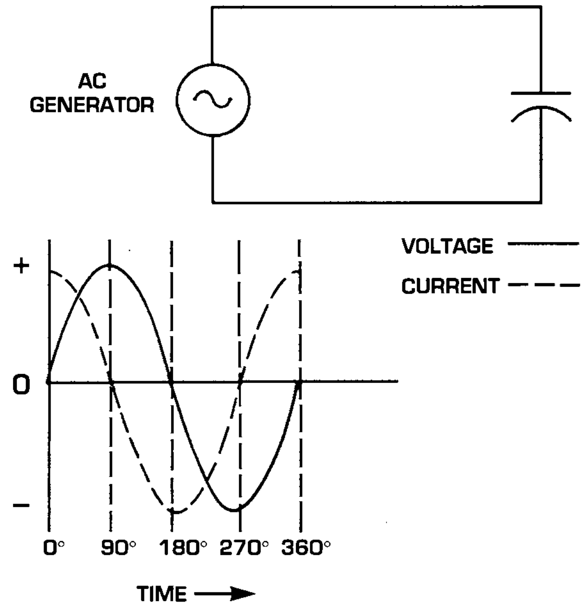
A Capacitor and its Schematic Symbol
Figure 7

If a resistor and capacitor are connected in series across a source of DC voltage, as shown in Figure 8, a very large current will flow momentarily as charges flow into one capacitor plate and drain off from the other. As the charges continue to accumulate, the voltage at the terminals of the capacitor will slowly rise until finally it equals the battery voltage. At that time, the voltages at both ends of the resistor are equal. From Ohm's Law (E=IR) we know that if no potential difference exists across the resistor then no current is flowing through it. The current flow in the circuit has therefore stopped; continuous current flow through a capacitor cannot be sustained because of the insulating material between the plates. However, during the time that the capacitor is charging or discharging, current can flow briefly.



Capacitor Charged Through a Resistor from a DC Source
Figure 8

Consider now the case where a capacitor is connected across a source of AC voltage as shown in Figure 9. At the beginning of a cycle, when the voltage from the generator starts to rise above zero, the capacitor passes a relatively heavy current as it begins to store charges. As the voltage continues to increase, the rate at which the capacitor draws current decreases until, finally, as the voltage reaches a maximum in the positive direction and starts again to decrease, the capacitor voltage will equal momentarily the voltage of the generator. At this instant, the current through the capacitor will be zero. As the generator voltage decreases, the capacitor voltage remains larger than the generator voltage and the capacitor discharges into the generator. This analysis can be carried through for the entire cycle of operation.



Capacitor Connected to AC Generator, Showing Phase Relationship of Voltage and Current
Figure 9

The waveform drawing of Figure 9 shows the relationship of the applied voltage to the capacitor current in this circuit. Note that the current is at a maximum when the voltage is at or very close to zero. The capacitor current is out of phase with the generator voltage; the current leads the voltage by 90 degrees. Notice that the capacitor **does** effectively allow alternating current to flow, even though the phase of that current is shifted by 90 degrees from the current that a resistance would pass.

The amount of alternating current that a capacitor will conduct depends on its ability to store charges (its capacitance). A capacitor therefore offers a certain amount of opposition to the flow of alternating current much as a resistance does. Because the capacitor affects the phase of the current, however, a different term, **capacitive reactance** (denoted by the symbol X_C), is used to define its opposition to the flow of current. The reactance of a capacitor is a function of its capacitance in farads and also of the frequency of the applied voltage. The following relates these variables:

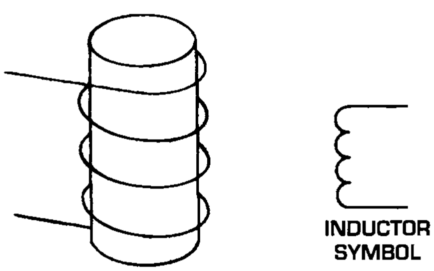
$$X_C = \frac{1}{2\pi f C} \qquad \text{(Eq. 13)}$$

where X_C = capacitive reactance in ohms
f = frequency in hertz
C = capacitance in farads
$\pi = 3.1416$

The equivalent value of capacitors connected in parallel is the sum of their individual capacitances. The equivalent for series-connected capacitors may be found by using the equation for parallel resistances (Equation 5). Note that these rules apply to capacitance but not to capacitive reactance. Capacitive reactances in series and parallel should be treated in the same way as series and parallel resistances respectively.

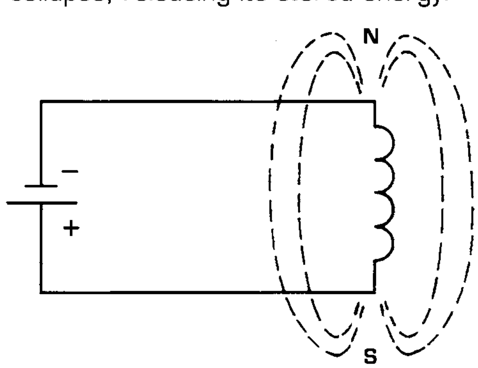
Inductance

Inductors are the second type of reactive element found in AC circuits. An inductor is formed by wrapping a number of turns of insulated wire around a form as shown in Figure 10. Current passing through a wire causes a magnetic field to be set up around the conductor. If a number of turns of wire are concentrated in a small area, the magnetic field generated by current passing through each individual turn adds to that of neighboring turns and a strong magnetic field is generated in the area of the coil.



An Inductor and its Schematic Symbol
Figure 10

Energy is required to create the magnetic field, and this energy comes from the current flowing through the coil. Figure 11 shows a coil connected to a battery. The current flowing from the battery through the coil sets up the magnetic field indicated by the dotted lines around the coil. The magnetic field will remain until the current is interrupted when it will collapse, releasing its stored energy.



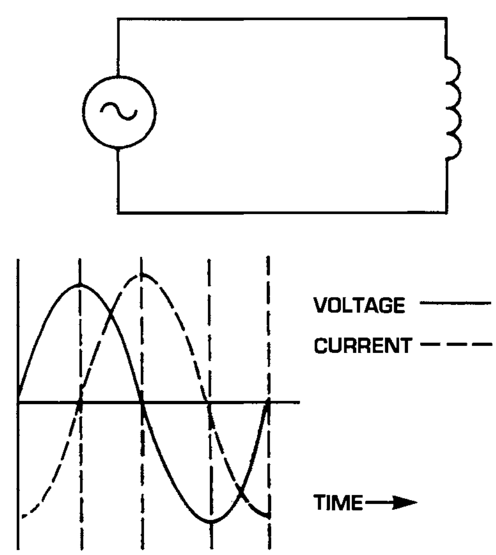
Inductor Connected to a Source of Direct Current
Figure 11

A coil operated on direct current is often referred to as an **electromagnet**. Like a common magnet, it has both a north and a south pole. Coils also have another interesting property: if passed through magnetic lines of force, a voltage will be developed at the terminals of the coil. This principle underlies the generation of electricity from mechanical motion. By passing a coil through a magnetic field, or by moving a magnetic field past a coil, electrical energy may be produced.

Referring again to Figure 11, when voltage is applied to the coil, current begins to flow and a magnetic field starts to build up. The magnetic lines of force cross some of the turns of wire and induce a voltage in the coil of the same polarity as that of the battery. This voltage is referred to as "back EMF." The result is that the potential difference between the battery and the coil is reduced and the current flow is less than it would be if the resistance of the coil wire were the only limiting factor. As the magnetic field nears its final size, fewer lines of force cross the turns of the coil, generating less back EMF and the current rises to its final value.

If the battery is now replaced by a resistor, the magnetic field begins to collapse, the lines of force cut through the turns of the coil in the opposite direction, and a voltage of the opposite polarity appears at the terminals of the coil. The energy stored in the magnetic field is converted to heat as current flows through the resistor. Coils, or as they are more frequently called, inductors, thus have an energy storage capability similar to that of capacitors. A useful rule to remember is that the back EMF of a coil is always of a polarity that opposes any change in the current flow.

The magnitude of the magnetic field set up by current passing through an inductor varies with the geometry of the coil as well as with the quantity of current. The characteristic energy storage capability of an inductor is its **inductance** (L), measured in henries.



Inductor Connected to a Source of Alternating Current, Showing Phase Relationship of Voltage and Current
Figure 12

When an inductor is connected to a generator of AC voltage, as illustrated in Figure 12, it will be observed that the current passing through the inductor is of a different phase than the voltage applied. When the voltage is at a maximum, very little current flows through the inductor because of the back EMF. The current gradually builds up until it reaches a maximum when the generator voltage nears zero. As the generator voltage moves toward its negative maximum, the collapsing magnetic field induces a back EMF in the coil of the same polarity as the generator, so the current again falls to zero. The waveform drawing of Figure 12 follows this process through a complete cycle, showing that the phase of the current in an inductive circuit **lags** the voltage by 90 degrees.

Because an inductor must repetitively store and release energy, it, like a capacitor, offers some opposition to the flow of alternating current. This opposition is termed **inductive reactance**. The amount of reactance exhibited by a particular coil depends on its inductance and on the frequency of the applied voltage, and may be found once the inductance is known by applying the following formula:

$$X_L = 2\pi f L \qquad \text{(Eq. 14)}$$

where X_L = inductive reactance in ohms
f = frequency in hertz
L = inductance in henries
$\pi = 3.1416$

Inductances in series may be added to find the total equivalent inductance. Parallel inductances may be calculated by using the formula for parallel resistances (Equation 5). Inductive reactances in series or parallel are always treated in the same way as series or parallel resistances respectively.

Impedance

Pure inductances, resistances, and capacitances are never found in practical electrical components. A resistor, particularly the type made from many turns of resistive wire, will exhibit some inductance. Also, the turns, which are wound in close proximity to each other, act like the plates of many tiny capacitors. Consequently, what purports to be a simple resistor will actually be a combination of all three types of circuit elements. In many cases, the unwanted characteristics are small enough that they may be ignored, but in other cases, they may have a significant effect on the performance of the circuit. In addition, many common electrical appliances require a combination of electrical components in order to operate properly.

In order to evaluate the total equivalent resistance or reactance exhibited by a circuit having a combination of components, a further concept is needed. Because the phase relationships of the current flowing through the various types of components is complex, the reactances and resistances cannot merely be treated according to the rules for series and parallel resistors. The phase of the current in such a circuit will vary between 90 degrees leading and 90 degrees lagging with respect to the voltage, depending upon the size of the various reactances.

The **impedance** (Z) of a circuit is the net opposition it offers to the flow of alternating current of a specified frequency. If the resistance, capacitive reactance and inductive reactance in a parallel circuit are known, the impedance of the circuit can be found from the formula:

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \qquad \text{(Eq. 15)}$$

where Z = impedance in ohms
R = resistance in ohms
X_L = inductive reactance in ohms
X_C = capacitive reactance in ohms

Note that the impedance will vary with frequency, since both X_C and X_L are frequency dependent. In practical AC power circuits, X_C is often small and can be neglected. In that case, the formula above simplifies to:

$$Z = \sqrt{R^2 + X_L{}^2} \qquad \text{(Eq. 16)}$$

Power and Power Factor

Power is determined in AC circuits in much the same way as in DC circuits as long as the current and voltage are in phase. For purely resistive loads, the power in watts is found by multiplying the RMS voltage by the RMS current in amperes (Equation 6). When inductive or capacitive elements are present in the load, however, the product of voltage and current no longer gives a true indication of the actual power being consumed. In such cases a correction factor must be applied, known as the **power factor** of the load. The **apparent power** is the product of voltage and current, expressed In volt-amperes. The **actual power** is expressed in watts. The power factor is defined as the ratio of the actual power to the apparent power:

$$\text{Power Factor} = \frac{\text{Actual Power (watts)}}{\text{Apparent Power (V}\bullet\text{A)}} \qquad \text{(Eq.17)}$$

In mathematical terms, the power factor is equal to the cosine of the angle by which the current leads or lags the voltage. If the current lags the voltage in an inductive circuit by 37 degrees, the power factor will be 0.8, the value of the cosine function at 37 degrees.

$$\text{Actual Power} = \text{VI cos. } \varnothing \qquad \text{(Eq.18)}$$

A power factor of 0.8 lagging is considered typical of most electrical circuits. If the phase of the current in a load leads the phase of the voltage, the load is said to have a **leading power factor**; if it lags, a **lagging power factor**. If the voltage and current are in phase, the circuit has a **unity power factor**.

It should be apparent from the preceding formulae that if the power factor of a load is low, more current will flow at a given voltage to deliver a specified power to the load than If the power factor is unity. This fact would be relatively unimportant in an ideal circuit where generators and conductors have no resistance. In practical applications, however, resistances do exist. The wire with which the generator coils are wound and the wires which carry the current from the generator to the load both have a finite resistance. Equation 9 shows that the power dissipated in a resistance is a function of the square of the current. A small increase in current will cause a much larger increase in the power dissipated as heat. Since electrical equipment, and insulation in particular, can withstand only a certain amount of heat, it is desirable to reduce the current flow as much as possible in delivering power to the load. With a power factor of 1.0, the current for a given load power is minimized, and the full capacity of the equipment may be utilized to provide useful power to the load.

In situations where the load consists primarily of large electric motors which are low power factor loads, it may not be practical to achieve a unity power factor. The generator then must be designed to withstand loads having low power factors. The excess current that flows in a circuit with less than unity power factor is known as the reactive component of the total current. The amount of the apparent power, which is due to this reactive component, is termed the **reactive volt-amperes**, and it represents the difference between the apparent power and the actual power. In power circuits, where voltages are often measured in kilovolts (thousands of volts), this reactive component of the apparent power is denoted by the abbreviation **KVAR** or **RKVA** — reactive kilovolt amperes. The reactive kV•A in a circuit may be found by the use of Equation 27, Table 1.

Energy

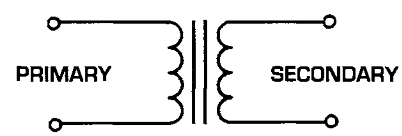
As with direct current, the energy used in an AC circuit is the product of the instantaneous power consumption and the length of time for which the power is expended. The watt-hour is the basic unit for measurement of this energy. The volt-ampere is not an appropriate unit to use in place of the watt for AC energy measurements because, depending on the power factor of the load, it may not give a true indication of the actual power consumed.

Transformation

A key reason for the use of alternating current instead of direct current in power distribution systems, other than the ease with which it may be generated, is that it may be readily converted from one voltage level to another with very little loss of power. The conversion process is **transformation** and the devices used to perform the conversion are called **transformers**.

There are many instances in which it is desirable to change voltages. The most important involves the transmission of electrical power over long distances. If a generator supplies a given amount of power to a load over a long pair of wires, a certain amount of power will be lost in heating the wires as a result of their inherent resistance. It has been shown that the power lost in a conductor increases as the square of the current. If the power is transmitted at low voltage and high current, a large portion of the power may be dissipated in the conductors rather than in the load. By transforming the generator output to a higher voltage, transmitting it via the wires and retransforming it to the original voltage near the load, the current carried by the conductors is reduced and hence the power loss will also be decreased.

Transformers consist of two coils located so that each intersects the magnetic field lines of the other. In practice, the coils are usually wound on the same core, made of a material such as iron which readily conducts magnetic lines of force. A schematic drawing of a transformer is shown in Figure 13. As alternating current passes from the generator through the first coil, called the **primary** winding, a magnetic field alternately is produced and collapses. The magnetic field lines are intersected by a second coil, the **secondary** winding, and the constantly changing field strength induces a varying voltage in the secondary winding corresponding to the primary voltage. Transformers cannot be used to change DC voltage levels. If direct current is applied to the primary, the magnetic field only changes during the time that the current rises to its final value. After that time, the magnetic field lines no longer move across the turns of the secondary, so no voltage appears at the transformer output terminals.



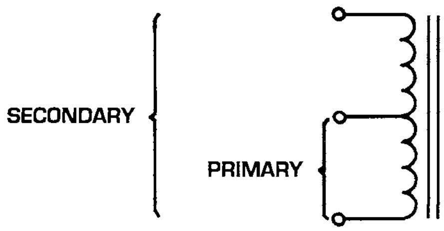
A Transformer
Figure 13

If the number of turns of wire in both windings of a transformer are the same, the voltage that appears at the secondary will be of the same magnitude as the voltage at the primary. If the number of turns is different, the voltage produced at the secondary is given by:

$$V_s = V_p \frac{N_s}{N_p} \qquad \text{(Eq. 19)}$$

where V_s = secondary voltage
V_p = primary voltage
N_s = number of secondary turns
N_p = number of primary turns

Transformers used to increase the input voltage are called **step-up transformers**; those used to decrease voltage are **step-down transformers**.



An Auto-Transformer
Figure 14

In some types of transformers, called **autotransformers**, only one winding is used. The coil is tapped at some point as shown in Figure 14. The turns of the "primary" actually form a part of the "secondary" winding. If a low voltage is applied to the primary winding, a higher voltage will appear across the secondary winding. Equation 19 may be used to calculate the secondary voltage, bearing in mind that the primary turns must be included when counting the number of secondary turns. The autotransformer may be used in reverse as well. If the input voltage is applied to the secondary, a lower voltage will appear across the primary. Autotransformers have the disadvantage that the secondary is not electrically isolated from the primary, and can therefore present a safety hazard at high voltages or when used improperly. They are very convenient, however, whenever a voltage. must be changed a small amount to suit a particular piece of electrical equipment.

SOURCES OF ELECTRICAL ENERGY

Although the existence of electrical energy sources has been assumed in the foregoing material, no detailed information about them has been presented. There are many types of sources ranging from the common flashlight battery to more exotic devices such as photoelectric cells and thermocouples. The two types most frequently employed are **batteries**, which produce electrical energy from chemical reactions, and **electromechanical generators**, which convert mechanical motion into electrical energy. The latter are of prime importance in power generating and distribution systems.

Batteries

Batteries are employed where it is desirable to store electrical energy for a period of time and yet have it instantly available whenever required. All batteries produce electricity from chemical reactions too involved to discuss here. One type of battery, the common "dry cell" or flashlight battery, releases electrical energy as a result of chemical reactions taking place between the compounds from which the cell was originally manufactured. The reaction proceeds only when current is being drawn. When all of the original materials have undergone the chemical reaction, no more electricity can be produced. The reaction in this type of battery is irreversible—the battery cannot be recharged. These batteries have a limited "shelf life." Some deterioration of the cell will occur even when current is not being drawn.

In another type of battery, the discharging process is reversible and the cell can be recharged from an outside source of electrical energy. Passing current through the battery in the opposite direction from that in which it flows during the discharge reverses the chemical reaction and restores the original energy to the cell. The process may be repeated many times, limited only by the destructive effects on the cells by secondary chemical reactions and physical deterioration. The common lead-acid storage battery used in automobiles is an example of a rechargeable battery. A portion of the battery's stored energy is used in operating the cranking motor when starting the engine. After the engine has started, an electromechanical generator driven from the engine supplies current to recharge the battery.

The output voltage of most batteries will decrease slowly as they are discharged. For this reason battery capacity is usually rated in ampere-hours rather than watt-hours. The number of ampere hours of current that a battery will deliver is dependent on its temperature (lower temperatures slow the chemical reactions and decrease the amount of available energy) and upon the rate at which it is discharged. Batteries have some internal resistance to the flow of current; if the battery is discharged at a high current, more of the energy will be dissipated in this resistance. Thus a battery will deliver considerably more total useful energy if discharged at low currents over a long period of time rather than rapidly at high current.

Electromechanical Generators

In the section above on inductors, it was stated that a voltage will be induced in a coil of wire moving through a magnetic field. This principle is put to use in the generation of electrical energy from motion. If a force is applied to continuously turn a coil in a magnetic field, an alternating voltage will be produced at the coil terminals. This voltage may then be transmitted through wires to a load where it can perform useful work. The mechanical energy required to move the coil is converted to electrical energy which, in turn, is converted to another form of energy at the load.

In practical AC generators, the magnetic field is produced by passing direct current through a second smaller coil of wire called the **field winding**. Only a small amount of current is necessary to "excite" the field coil. The coil in which the electricity is actually produced is called the armature. Since the field coil can be made appreciably smaller than the armature, the latter is often constructed on a stationary form and the field coil made to rotate inside it.

The current required to excite the field is supplied to the rotating coil by means of **collector rings**, which are rings of metal insulated from the shaft on which the coil rides and connected to the ends of the field winding. The rings rotate with the shaft and carbon brushes make contact between them and the source of the field current, which may be an external battery derived from a belt or direct driven DC generator or from a small rotating AC generator and rectifiers. See Figure 16 for the several methods.

Four-pole and six-pole field coils are commonly used. Adjacent poles are of opposite magnetic polarity, so that as the field turns within the fixed armature, or **stator**, winding, the magnetic field at any given point is reversed each time a pole face passes. The angular velocity of the field coil can thereby be reduced for a given output frequency, since one cycle of output power is produced each time a pair of magnetic poles passes the stator coil.

The field current often is taken from the output of the generator itself. When the field coil is set into motion, a small amount of electricity is available at the generator output as a result of the residual magnetism in the field coil core material. This small current is supplied to the field coil, adding to the residual magnetic field. More electricity is then produced until after a few rotations the full field current is flowing and full generator output is available. When operating, the field coil uses only a minute fraction of the generator output current.

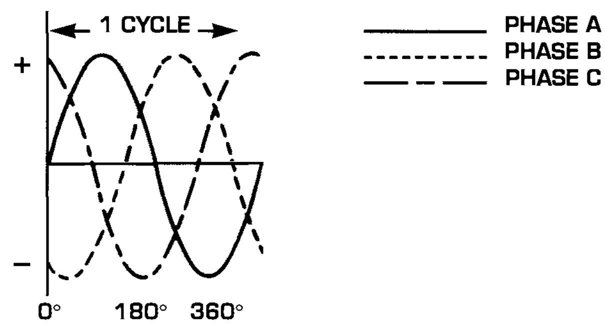
Since the output of the generator is an AC voltage and the field must be excited with DC, rectifiers are used to change the AC voltage to DC before applying it to the field. A **rectifier** is a device which exhibits a very high resistance to the flow of current in one direction and a very low resistance to the flow in the opposite direction. For practical purposes, the rectifier only permits current to flow in one direction in the circuit, and thus it can convert AC into pulsating DC, which is adequate for field excitation. Modern generators use semiconductor rectifiers to accomplish the conversion. A separate exciter with rotating diodes permits construction of a "brushless" excitation system.

Voltage Regulation

The voltage at the output of the generator armature winding is dependent on the field coil angular velocity and the intensity of the magnetic field produced. Since it is usually desirable to maintain a constant frequency at the output of the generator, the velocity cannot be varied to adjust the output voltage. The field current is commonly controlled to obtain the desired voltage.

In modern generators, the field current is adjusted by **silicon controlled rectifiers** (SCRs). These devices, like ordinary rectifiers, pass current in one direction only, but they also include a "gate" terminal to control the flow of current. When the gate terminal is not energized, the rectifier conducts no current, but when a voltage is applied to the gate terminal, current is passed in one direction. By applying gate voltage at various points on the AC cycle, pulses of current may be fed to the field and the average field current varied. During the remainder of the cycle the magnetic field surrounding the field coil collapses, thus inducing current in the coil. A second rectifier is connected across the field terminals to allow a path through which this current may flow.

This gate of the SCR is controlled by a **voltage regulator** circuit which senses the generator output voltage and automatically adjusts the field coil current to maintain the desired output. If a load is applied to the generator, the output voltage will drop slightly. The voltage regulator circuit causes the SCR to conduct for a longer period of time during each cycle, thus increasing the field current and restoring the output voltage to the desired level.



Phase Relationships in a Three-Phase Circuit
Figure 15

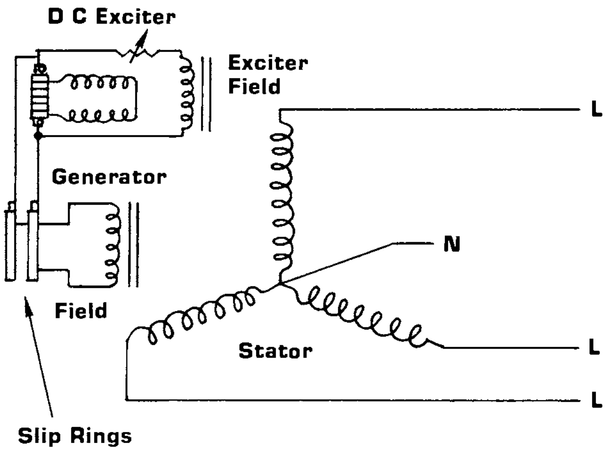
Phase Arrangement

The armature of a generator may be a single coil, or there may be three coils spaced at 120 degree intervals around the frame. In the latter case, the output of the three coils will exhibit a phase difference, since the magnetic poles of the field coil pass the three armature coils at different times. The output waveforms of each of the three coils are shown in Figure 15. Generators constructed in this manner are called **three-phase generators**, while those having only one armature coil are called **single-phase generators**. Three-phase machines are common where a large amount of electrical power is to be generated.

A **three-phase system** is an AC circuit to which is applied three voltages of the same frequency but displaced electrically by one-third of a cycle or 120 degrees. The three generator windings used may be connected in either a delta or a wye (star) configuration.

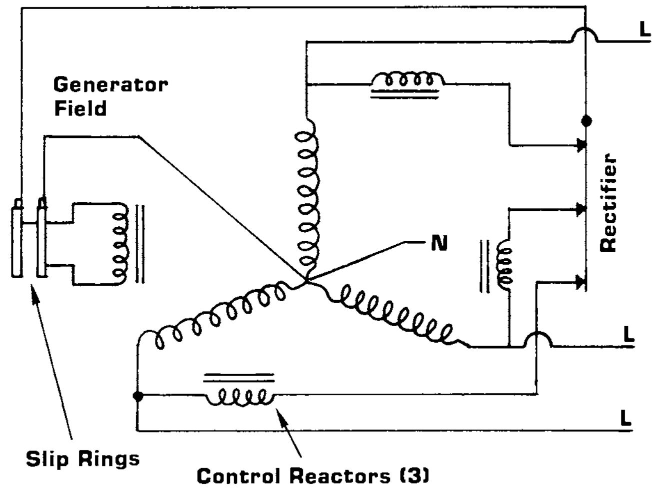
The **wye** (star) connection (17 A, C) has a **neutral** point, often connected to earth. The **delta** (mesh) connection (17 B, D) does not have a neutral point. Coils generally have a midpoint. A midpoint of **one**

Methods Of Field Excitation



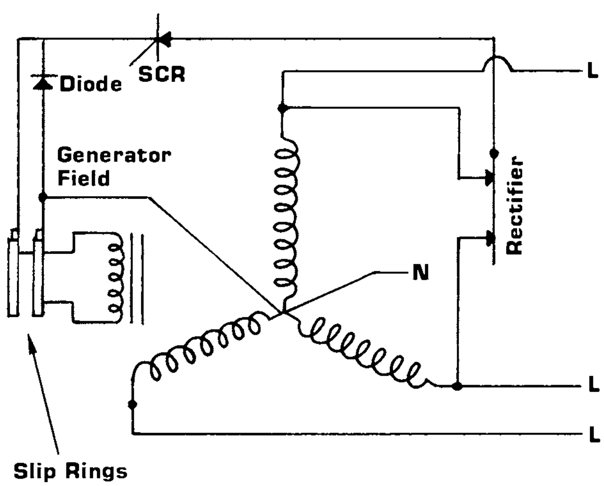
D C Exciter, Belt Driven, Supplies Rotating Field Through Slip Rings and Brushes.

A



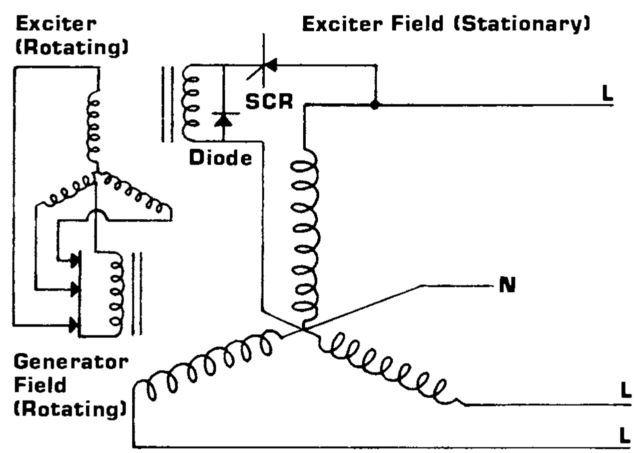
Three-Phase Half Wave Rectifier Supplies Rotating Field Through Control Reactors And Slip Rings.

B



Two-Phase Half Wave Rectifier Supplies Rotating Field Through Control Rectifier (SCR) And Slip Rings. Diode Maintains Self-Induced Field Current When SCR Is "Off".

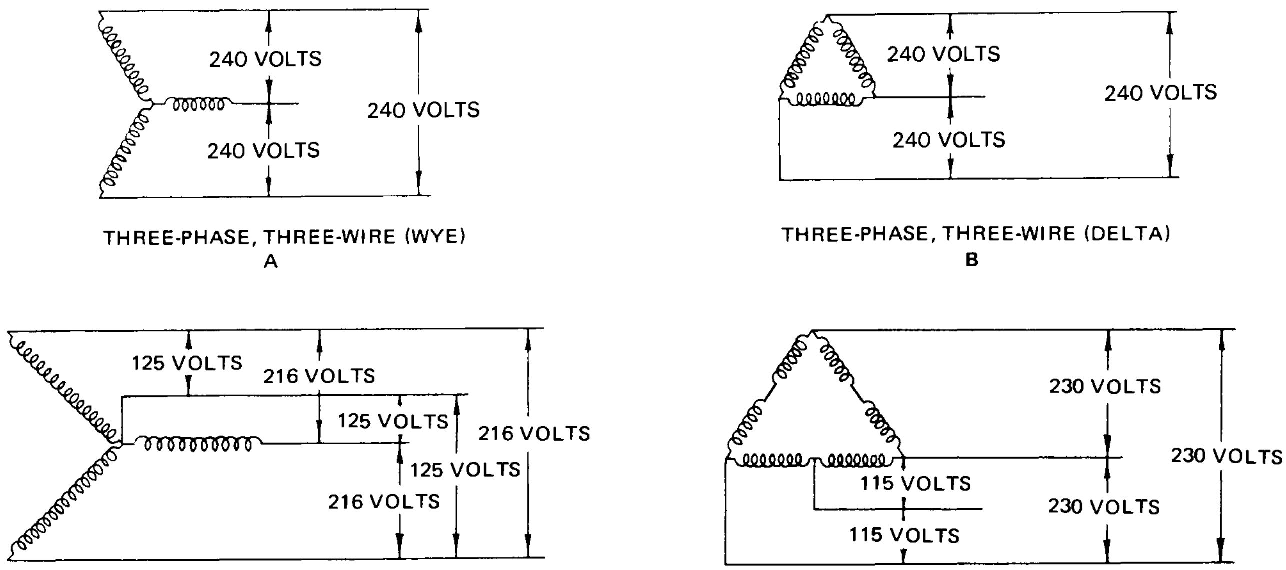
C



"Brushless" Rotating Exciter Supplies Generator Field Through Rectifiers. Exciter Field Supplied From Generator. Output Controlled By SCR. Diode Maintains Exciter Field Current when SCR Is "Off".

D

Figure 16



THREE-PHASE, THREE-WIRE (WYE)
A

THREE-PHASE, THREE-WIRE (DELTA)
B

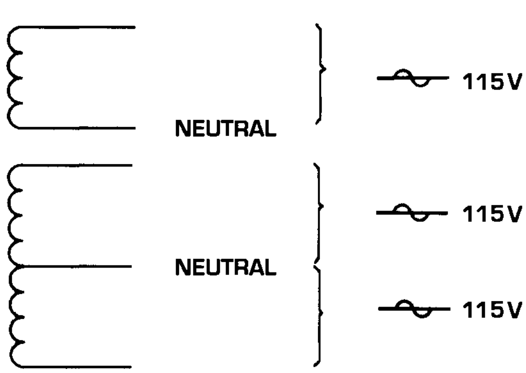
THREE-PHASE, FOUR-WIRE (WYE)
C

THREE-PHASE, FOUR-WIRE (DELTA)
D

Three-Phase Connection Systems
Figure 17

coil may be connected to earth. Generators rated above 300 kW are generally constructed in wye configuration. Generators rated below 300 kW may be either wye or delta. If all of the coil ends terminate in accessible connections, field reconnection from wye-to-delta or delta-to-wye is possible. Terminal voltages would change.

A **single-phase AC circuit** is one to which one voltage at a given frequency is applied. Such circuits are used mostly for lighting and fractional horsepower motor loads and are served by two wires with one being neutral (earth or ground), or by three wires, one neutral and the other two operating with equal voltage relative to neutral. These two types of single-phase circuits are shown in Figure 18. The coils supplying the power may be either the secondaries of step-down transformers or the stator windings of a generator set.



Two- and Three-Wire Single-Phase AC Circuits
Figure 18

It is also common to find combination services entering an existing building. An example is the use of a single-phase three-wire service for lighting loads and a three-phase three-wire service for motor loads. The load distribution on each of the three phases in a given installation should be determined, as well as the amount of single-phase power required and the manner in which it is to be distributed on the three available phases of the generator set. If any of the three phases is required to supply excessive single-phase power in addition to the portion of the three-phase load which it carries, the generator may be overloaded. The connection of single-phase loads will then have to be redistributed more evenly among the available phases or, if existing wiring makes this impractical, a larger size generator will have to be specified to carry the extra single-phase load.

DC Generators

Direct-current generators are rarely used today except in certain special applications. A notable exception, of course, is in motor vehicles, where direct current is needed to recharge the storage batteries which supply power for engine cranking. A DC generator is usually constructed with the field coil stationary. The armature consists of many coils of wire, set at small angles around the shaft, each connected to a pair of **commutator** bars mounted on insulators near the end of the shaft. As one of the coils passes the field pole pieces, a voltage is induced in it. At the same time, brushes contact the commutator bars connected to the ends of that coil, allowing current to flow into the load. As the first coil of the armature moves away from the pole pieces, a second coil moves into place, and the brushes simultaneously make contact with the commutator bars connected to this second coil. If a sufficient number of armature poles are provided, a nearly steady flow of direct current is produced.

When direct current is required and a source of AC power is available, rectifiers are usually employed to convert the AC power to DC instead of using less efficient DC generators. In fact, modern automotive electrical systems use AC generators (alternators) and semiconductor rectifiers in place of DC generators which were standard in the past.

APPLICATIONS OF ELECTRICAL POWER

Lighting

One of the earliest and still one of the most important uses of electrical power is in lighting. The original type of device used to convert electrical energy to light, the **incandescent lamp**, is commonplace in an improved form today. Electrical current is passed through a very thin resistive **filament**, heating it to a white-hot glow. Although the incandescent lamp is inefficient because much of the energy is lost in producing unwanted heat, its simplicity and low cost have made it extremely popular.

The **fluorescent lamp** has replaced the incandescent type in many applications. This lamp takes the form of a long glass tube with a small heating element at either end. The tube is filled with mercury vapor and the inside of the glass is coated with a fluorescent material. The heaters are used both to assist in starting the lamp and as electrodes when the lamp is operating. A voltage is applied between the heater-electrodes and the mercury vapor is ionized as a stream of electrons flow the length of the tube from one electrode to the other. The ionized gas emits ultraviolet light which strikes the fluorescent coating and causes it to give off visible light. A ballast transformer is used to supply low voltage to the heaters and to limit the current through the lamp.

Heating

As electrical power has become increasingly economical, the very large amounts of energy required for electrical heating applications have become feasible. From the enormous electric furnaces used in the production of steel to small electric ranges or home heating systems, electricity provides a clean and easily controlled source of heat.

In most heating devices, heat is produced from electrical energy by the simple process of passing current through a resistive element. In some cases, electricity is used to produce a varying magnetic field which, in turn, heats the material through which it passes, a technique used in induction furnaces. The amount of heat produced may be controlled by the length of time that the heating device passes current or by varying the amount of current permitted to flow. Automatic controls may be constructed to switch heating elements on and off according to the heating load demand, or to control the current flow. The latter type of system is called "proportional control." Thermostats, devices which sense the ambient temperature and compare it to a preset level, are used as control devices.

Mechanical Power

Electric **motors** are used to convert electrical energy into mechanical motion. If current is passed through a coil located within a magnetic field, the coil will tend to change its orientation until its field aligns with the external magnetic field. By mounting the coil on a shaft which is free to rotate, and by periodically reversing the direction of current through the coil or the sense of the external magnetic field, the coil can be forced to rotate continuously. In three-phase AC motors a revolving magnetic field is supplied by a three-phase stator winding. The stator and rotor coils have a number of poles around their circumference, the number being inversely related to motor speed. The rotor revolves as it attempts to align itself with the applied magnetic field.

Polyphase AC motors are of two basic types: the first of these is the **induction motor**. Power is applied to the stator winding and current is induced in the rotor windings by the magnetic field of the stator. In **squirrel cage motors** no connections are made to the rotor winding. In **wound rotor (slip ring) motors** the rotor winding is connected to an external variable resistance by means of slip rings and brushes.

Induction motor speed is not directly synchronized to the AC power frequency. They operate somewhat below synchronous speed, depending on the load applied. A second basic type of AC motor is the **synchronous** motor. These have a salient pole field winding whose current is supplied by a DC exciter. They run at synchronous speed regardless of load changes. Synchronous speed is determined by the frequency of the AC voltage and the number of poles in the field.

MEASUREMENT TECHNIQUES

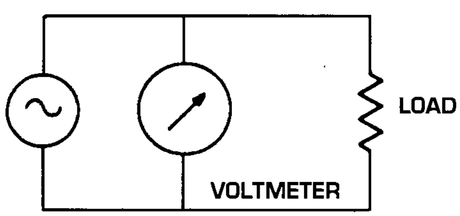
In order to apply electrical power intelligently, one must be able to accurately measure such quantities as voltage, current, power, power factor, phase and frequency.

Voltage

Voltage in electrical circuits is measured by means of devices called **voltmeters**. They consist of a coil of wire mounted on a rotatable shaft and positioned between the pole pieces of a permanent magnet. A pointer is attached to the shaft in such a manner that as the coil and shaft rotate, the pointer passes in front of markings on a dial scale. When current passes through the coil it moves to align its magnetic field with the external field, causing the shaft and pointer to rotate against the force of a spring. The position at which the pointer comes to rest is an indication of the strength of the current flow. Since the coil has a fixed resistance, each value of current corresponds to a specific voltage. The dial scale may therefore be directly calibrated in volts. Meters are available in a wide range of full-scale voltages. Voltmeters have a very high coil resistance so that very little current is drawn from the circuit to which they are connected.

A voltmeter of the type described will work properly on DC but not on AC voltages. Since AC voltages reverse every fraction of a second, the direction of pointer movement would also attempt to reverse. Because of its inertia, the coil and pointer assembly cannot follow these rapid movements and it remains nearly at rest. For AC voltage measurements, meters are usually supplied with an internal rectifier which converts the AC voltage to DC. AC voltmeters for the measurement of very high voltages may also be equipped with a **potential transformer** which reduces the voltage to be measured by a known ratio to a level suitable for the meter movement.

Practical voltmeters used in AC measurements are calibrated to read RMS voltage, assuming that the waveform is sinusoidal, which is very nearly the case in most applications. Special voltmeters are available to measure the peak voltage of AC waveforms. **Oscilloscopes**, devices which provide real-time graphic displays of voltage versus time, may be used to measure the amplitude and duration of **transients** — short abnormal variations in amplitude.

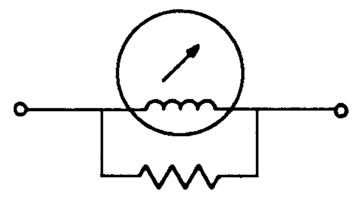


Proper Connection of a Voltmeter
Figure 19

Voltmeters are always connected in parallel with the circuit to be measured, as shown in Figure 19. If the output voltage of a generator is to be determined, the voltmeter is connected directly across the output terminals. If the voltage at the input of a motor is to be measured, the voltmeter is connected across the motor terminals. To measure the voltage drop through a pair of conductors, the voltmeter is connected first across the generator end of the pair and then across the load end. The second reading is subtracted from the first.

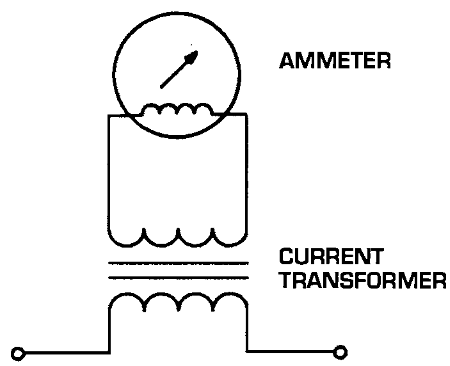
Current

Current is measured through the use of **ammeters**, which are very similar in construction to voltmeters. The coil resistance of ammeters is very low, however, since the current to be measured is allowed to flow through the meter coil. A high resistance coil would result in a large voltage drop across the meter, which would drastically reduce the current flow in the circuit to be measured. The meter scale is calibrated directly in RMS amperes (or some fraction thereof) instead of in volts. As with voltmeters, rectifiers are included if the meter is intended for measurement of AC currents. Ammeters designed to measure very large currents may have a fairly low-current basic movement shunted by a low resistance, as shown in Figure 20.



Ammeter with Shunt Resistor
Figure 20

Most of the load current flows through the shunt resistor and only a small fraction passes through the meter coil. The scale may then be calibrated for a much higher current. Another type of high-current ammeter uses a **current transformer**, as in Figure 21. The high current flowing in the transformer primary winding is transformed to a lower current in the secondary, which is connected to the meter. If the turns ratio of the transformer is known, the factor by which the current is scaled can be determined.



Ammeter with Current Transformer
Figure 21

A special case of the current-transformer ammeter is the clamp-on or tong-type meter. The secondary of the current transformer is contained inside a tong-shaped probe which can be clamped around a current-carrying wire. The wire is surrounded by a magnetic field when current is flowing through it, and it forms the primary of the transformer. Tong-type ammeters are very useful in making rapid measurements since the circuit does not have to be broken to insert the meter. Conventional ammeters must be inserted in series with the circuit so that the current can pass through the meter coil and its shunts.

Power and Power Factor

Power in DC circuits may be determined by measuring the voltage and current and multiplying the results, since $P = I E$ (Equation 6). Apparent power in AC circuits, measured in volt-amperes, may be found in the same way. Actual power in watts, however, must take into account the power factor. **Wattmeters** are available which simultaneously measure voltage, current and power factor and automatically multiply the results to give an indication of true power. They employ two coils, one for voltage and one for current, mounted in such a way that the pointer deflection is a product of the two quantities with correction made for any variation in phase angle between the two waveforms. To prevent damage to the instrument, care must be taken to ensure that the rating of neither the voltage nor the current coil is exceeded, as the pointer may not indicate an overload condition.

Power factor may be calculated by measuring both the actual power and the apparent power. The ratio of the two values yields the power factor (Equation 17). Power factor may be measured directly in three-phase circuits with a clamp-on power factor meter. This device contains a current transformer and three voltage leads. It can give a reasonably accurate indication of both leading and lagging power factors.

Phase and Frequency

In three-phase AC circuits, the phase of each leg lags the phase of the preceding leg by 120 electrical degrees. If the three legs are denoted A, B, and C, then leg B will lag leg A by 120 degrees and leg C will lag leg A by 240 degrees. Since it is not always possible to trace the leads back to the generator to find out which one is connected to each phase, an indicating device may be used to determine the **phase sequence**. The device will indicate, with reference to a given phase, which of the other two phases lags by 120 degrees and which lags by 240 degrees. The phase sequence may thus be deter-mined. Such measurements are important when connecting devices such as electric motors which will work properly only when their leads are connected to the proper phase leads of the power source. Three-phase motor rotation can be reversed by reversing any two phase connections to the motor.

Simple indicators are also available to indicate over a limited range the frequency of an AC waveform. These devices employ vibrating reeds, each resonant to a particular frequency. For 60 Hz systems, reeds are usually chosen which resonate at 58,59,60,61, and 62 Hz. If 60 Hz energy is supplied to the meter, the reed resonant at 60 Hz will vibrate, giving a visible indication of the power frequency. If the generator frequency is slightly too high or too low, one of the other reeds will vibrate, indicating that the speed of the generator must be adjusted to restore it to operation at the proper frequency.

Frequency can also be measured by a vane-type of meter which uses a capacitor, resistor and rectifier. Alternating current supplied to the internal circuit results in a small direct current of very low voltage that is directly proportional to frequency. Essentially, the instrument indicates the resulting DC current, but the scale is calibrated in hertz. These instruments are available in three ranges: From about 47 to 53 Hz, from about 56 to 64 Hz, and from about 45 to 65 Hz.

Digital readout frequency meters are also used. These are comparative devices which constantly count the cycles per unit of time and at preset intervals display the result. Other types average the frequency over some preset interval of time and then display the result.

III. GENERATOR SETS

KW AND KV•A REQUIREMENTS OF LOAD

In selecting the correct size generator set for a given load, the load kW requirements are naturally the most important factor. The generator set should have sufficient capacity to supply maximum load conditions after the load factor has been taken into account, but it should also have reserve capacity to allow for motor starting and for some future expansion in load where indicated. Standard practice is that the generator set have 20 to 25 percent more capacity than required for actual maximum load conditions. It is assumed that single-phase loads will be evenly balanced on the phases of a three-phase generator set. If this cannot be accomplished, a larger capacity generator may be required to handle the extra kV•A load on the phases carrying single-phase circuits in addition to the normal three-phase load. This problem is considered in more detail in a later section of the present chapter. In situations where the power factor of the load is significantly below the value at which the generator set kW output is rated, a larger capacity generator may be required to supply the additional kV•A. The line current requirements of the actual load must never exceed the generator nameplate rating.

GENERATOR VERSUS ENGINE SIZE

Normally a generator set is furnished with a generator which matches the engine output capability. Where power factors are low, however, it may be advantageous to select an oversized generator rather than specify the next larger size generator set. Since the engine horsepower output is related to kW and not necessarily to kV•A, for a given engine output, an oversized generator will supply essentially the same kW output as a normal generator, but will be able to tolerate a higher value of reactive kV•A because of its greater current-carrying capacity.

MOTOR STARTING REQUIREMENTS

The generator set must include enough kW capacity to handle the electric motor operating load. Additionally, the generator set must accept the motor starting kV•A load and the starting kW load without excessive voltage reduction. An oversize generator is useful where motor starting kV•A demand is high in relation to the actual starting kW demand. A larger than normal generator can also provide increased inertia-developed energy, thus reducing speed and voltage drop during the motor starting period.

Centrifugal pumps, blower fans, and some very high inertia loads may take advantage of an electric motor characteristic which provides two times normal torque during the starting period. The kW demand of motors starting these loads may far exceed the kW equivalent of the motor nameplate horsepower. The generator set must be capable of supplying this short term demand without excessive speed or voltage reduction. Motor characteristics and speed-load characteristics are necessary to accurately predetermine the effect of these loads.

MULTIPLE GENERATOR SETS

In some situations, the use of more than one generator set is mandatory; in others, it may prove more economical. In the former category are installations in which the prime power source is a generator set, and failures cannot be tolerated. A second generator set capable of carrying critical loads should be made available in case of failure of the primary set and for use during prime set maintenance periods.

Cases where multiple generator set installations may prove more economical are those where there is a large variation in load during the course of a day, week, month, or year. Such variation is typical in plants in which operations are carried on primarily during the day while only small loads exist at night. The more closely a generator set comes to being fully loaded, the greater the fuel economy per kilowatt produced. Therefore, the use of a small unit to power light off-hour loads will often result in long-term fuel economy.

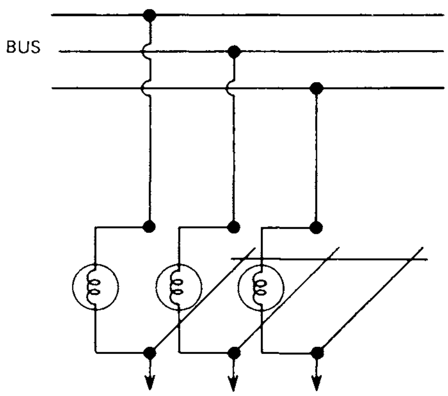
In installations where the load does not vary to the extremes encountered between day and night conditions, it is sometimes profitable to share the load between several small units operating in parallel rather than using a single large set. One or more of the units may then be shut down when the load is lighter, thereby loading the other units more nearly to capacity. An instance in which this type of system shows an advantage is where load demand is seasonal.

PARALLEL OPERATION GENERATOR SETS

Two or more AC generator sets may be operated in parallel provided three fundamental conditions are satisfied:

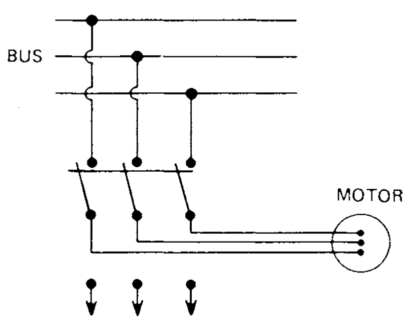
1. Their voltages must be the same.
2. Their frequencies must be the same.
3. Their phase sequences must be the same.

The first condition must be satisfied at the time that the generator sets are specified, and also by adjusting the output voltage controls of each unit when put into operation. The phase sequence requirement can be satisfied at the time the units are connected together by observing the manufacturer's instructions regarding phase sequence. The lamp circuit in Figure 22 may be used as a test device for proper sequence if other information is not available. Before connecting a generator set to a power bus being supplied by other units, the light bulbs should be observed with all machines operating. If all the bulbs become light, then dark, then light again simultaneously, the phase sequence is correct. If it is incorrect, the lights will never all be light or dark at the same time. If the latter is the case, two of the three lines from the generator set must be interchanged. If the machines are operating at precisely the same frequency, the intensity of the lights will not change. The frequency of the generator set under test may be varied slightly to perform the check.



Lamp Connections for Phase Sequence Test (use resistors in series with lamps for voltages over 120 volts) Figure 22

A second method of comparing phase sequence is shown in Figure 23. A small three-phase induction motor is connected alternately to the power bus and to the generator set under test. If the motor rotates in the same direction in both cases, the phase sequence is correct. If not, two of the leads from the generator set should be interchanged.



Connections for Phase Sequence Tests Using Small Induction Motor Figure 23

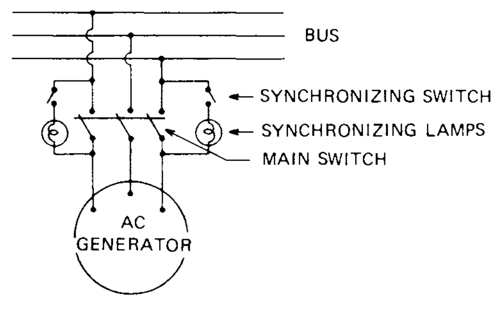
Adusting Frequency-Synchronization

For any given generator, the frequency is entirely controlled by engine speed.

$$F = \frac{\text{Poles} \times \text{RPM}}{120}$$

Engine governor speed must therefore be adjusted to match generated frequency before actually paralleling the generator with other generator sets.

The process of **synchronization** involves the measurement of the frequency difference between a generator set to be connected to a bus and those already supplying power to the bus. Engine tachometers are not sufficiently accurate to set the generator sets to precisely the same frequency. Manufacturers are able to supply switchgear with built-in lamps to indicate when the oncoming generator set is operating at the correct speed. Figure 24 shows a typical circuit. When a frequency difference exists, the lamps will flicker at a rate equal to that difference. As the generator set speed is slowly increased or decreased as required, the lamp flicker rate will become slower. When the flicker has slowed to approximately two-second intervals, the connecting switch should be thrown at the estimated center of one of the dark periods.



Synchronizing Lamps for Parallel Operation Figure 24

Synchronization may also be accomplished by use of a **synchroscope,** a device which indicates the difference in phase and frequency of two circuits. It usually has a revolving pointer and a dial marked to indicate whether the oncoming generator frequency is high or low. The connecting switch is thrown when the pointer is stable in the center (zero phase difference) position.

Once the alternating current generator sets are in parallel, load division between units is entirely controlled by the speed setting of the engine governors. Increasing the speed setting of one engine will cause it to absorb more load, and other generator sets in the system will be relieved of some load. Conversely, decreasing the speed setting of one engine will cause it to decrease load. Other generator sets will absorb that load. All load can be removed from a generator by slowly decreasing the speed setting. If the speed setting is moved lower than the no load point, that generator set will absorb power from other units which will continue to drive it at synchronous speed. It is impossible to have stable parallel operation if more than one unit in the system is set for zero speed droop (isochronous) operation unless the governors are the electronic load sharing type. Three percent speed droop governors perform very well in parallel systems where precise load share is not required.

BALANCING OF LOADS ON AVAILABLE PHASES

If the electrical distribution system served by a three-phase generator set consists entirely of three-phase loads, the system is balanced. The coils making up the generator's three phases each supply the same amount of current to the load. If single-phase loads are added to the three-phase load, however, a condition of unbalance will exist unless the single-phase loads are equally distributed among each of the three phases of the generator set.

In many applications, balancing of single-phase loads may not be practical. If these loads are relatively small (10 percent or less of the generator set three-phase kV·A capacity), unbalanced single-phase loading is not cause for concern provided that each of the three line currents does not exceed the generator set rating. The following problems illustrate the method of determining the maximum single-phase load which may be safely drawn from a generator set supplying single-phase and three-phase power simultaneously. Table 2 gives formulas which are useful in making calculations of kV·A for various phase configurations.

Problem 1:

Find the amount of single-phase power which can be safely drawn from a three-phase 125/216 volt four-wire generator set rated to deliver 100 kW at a 0.8 power factor. The coil current rating of the generator set is 334 amperes. Assume that the single-phase load is connected from one line to neutral and has an operating power factor of 0.9 lagging, and that the generator set is also supplying a three-phase load of 50 kW at a power factor of 0.8.

Solution:

1. Find the current drawn from each of the lines by the three-phase load.

$$P = \frac{\sqrt{3}E \times I \times P.F.}{1000}$$

$$I = \frac{P \times 1000}{\sqrt{3} \times E \times P.F.} = \frac{50 \times 1000}{1.73 \times 216 \times 0.8} = 167 \text{ amperes}$$

2. Find the coil current capacity remaining for the single-phase load.

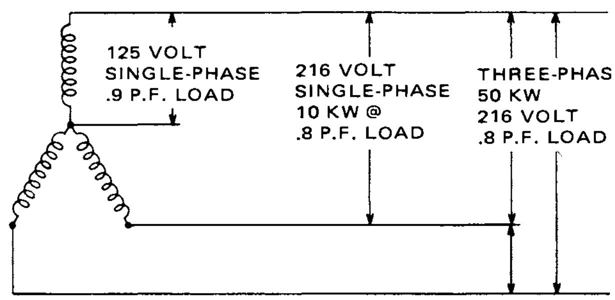
$$334 - 167 = 167 \text{ amperes}$$

3. Find the single-phase power available.

$$P = \frac{E \times I \times P.F.}{1000} = \frac{125 \times 167 \times 0.9}{1000} = 18.8 \text{ kW}$$

Problem 2:

The generator set is rated to deliver 100 kW at a 0.8 power factor. It is a three-phase machine with a coil current rating of 334 amperes. The three-phase load to be supplied is 50 kW at 0.8 power factor. The single-phase load consists of both 125 and 216 volt circuits. The 125 volt load has a power factor of 0.9 and is connected from neutral to one leg. This leg is common with one of the two supplying 10 kW at a 0.8 power factor to the 216 volt load (see Figure 25).



Circuit Diagram, Problem 2
Figure 25

Solution:

1. The current drawn from each line by the three-phase load is found by the procedure used in step 1 of problem 1 to be 167 amperes.

2. The coil capacity available for single-phase loads is again 167 amperes.

3. Find the 216 volt single-phase load current.

$$I = \frac{P \times 1000}{E \times P.F.} = \frac{10 \times 1000}{216 \times 0.8} = 58 \text{ amperes}$$

4. Find the coil current capacity remaining for the single-phase 125 volt load.

$$167 - 58 = 109 \text{ amperes}$$

5. Find the 125 volt single-phase power available.

$$P = \frac{E \times I \times P.F.}{1000} = \frac{125 \times 109 \times 0.9}{1000} = 12.3 \text{ kW}$$

IV. AUXILIARY EQUIPMENT

CIRCUIT BREAKERS

Circuit breakers are devices which protect generating equipment and distribution lines from damage which may result from excessive current flow. They are available in a wide range of current ratings. When the rated current is exceeded by a small amount, the circuit breaker automatically "trips" and opens the electrical circuit. Normally they are of the dual type, tripping instantaneously on heavy overloads such as short circuits, but only after a certain time interval on lesser overloads. The time delay effect prevents their tripping on normal momentary overloads such as motor-starting currents.

Voltage Ratings

Several different types of circuit breakers are available. The selection of the correct type for use with a given generator set is made on the basis of line voltage and rated full-load line current. For all voltages less than 600 volts either an air circuit breaker or a molded-case thermal magnetic breaker may be used, depending on line current. For voltages over 600 volts, oil or air breakers must be used regardless of line current.

Circuit Breaker Trip Ratings

Full-load three-phase line current may be calculated by substituting the generator set kW, power factor and voltage ratings in the following formula:

$$I = \frac{kW \times 1000}{\sqrt{3} \times E \times P.F.}$$

From this formula a constant can be determined for each voltage if a three-phase system at 0.8 power factor is assumed. This constant when multiplied by the generator set kW rating will yield line current.

Voltage	Constant
115	6.27
125	5.28
200	3.61
230	3.14
240	3.01
380	1.90
400	1.80
460	1.57
480	1.50
575	1.26
2400	0.30
4160	0.17

Once line current has been determined, final selection of the circuit breaker trip rating may be calculated from the formula:

Line current x percent overcurrent = trip rating

The percent overcurrent is the minimum percentage of rated continuous current flow which will cause the breaker to open. The ideal overcurrent percentage to use in determining the trip rating is 125 percent, but any figure in the range from 110 to 150 percent may be used to arrive at a trip rating which is standard for commercially available breakers. Because of the inherent time delay in most breakers, the percent overcurrent figure is pertinent for continuous overloads only. Considerably larger current surges will not actuate the breaker.

Circuit Breaker Selection

The largest current trip rating available in a thermal-type circuit breaker is 2000 amperes. This breaker type is suitable for generator sets with line currents up to 1800 amperes. A 200 ampere safety factor is allowed for high ambient temperatures. For higher line currents magnetic breakers must be used.

Once the circuit breaker type has been selected, the type of switchgear may also be determined. Magnetic, thermal and oil circuit breakers larger than 1200 amperes require floor-standing switchgear because of their physical size. Thermal circuit breakers rated at 1200 amperes and smaller can be used with wall-mounted switchgear cabinets. However, other switchgear components may still dictate the use of a floor-standing arrangement.

Special Circuit Breaker Features

There are several commonly-used circuit breaker modifications available. One of these is the shunt trip feature. This modification allows for tripping the breaker with an electrical signal from a remote location. For example, the shunt trip on each breaker can be connected to the engine low oil pressure and high water temperature alarm contactors so that in the event of an engine malfunction or overload, the circuit breaker for the generator set will be tripped. This arrangement is particularly recommended when generator sets are to operate in parallel, as it will prevent the affected set from being motored by other machines on the power bus. The shunt trip has an auxiliary contact to provide for breaking the energizing circuit after the breaker has tripped.

An undervoltage trip is sometimes a desirable modification for the circuit breaker. This device automatically actuates the trip mechanism when line voltage drops 40 to 60 percent below normal voltage. It cannot be used, however, with automatic start-stop systems.

INDICATING INSTRUMENTS

Switchgear selected for use with a generator set should include, in addition to the circuit breaker, a number of indicating devices to enable the operator to monitor system performance. A minimal system would provide an ammeter with a phase-selector switch to permit monitoring of current on any of the three lines, and a voltmeter to monitor generator output voltage. Any necessary current and potential transformers would, of course, be included.

Optional additions to these basic requirements include a frequency meter, a wattmeter, an alarm panel to provide a visual indication of high water temperature and low oil pressure, a set of synchronizing lamps and switch to permit parallel operation, a governor switch for use with a governor synchronizing motor, and a more elaborate meter switch to permit monitoring of both voltage and current on any of the three phases.

TRANSFER SWITCHES

For standby systems, a means must be provided to switch the load from the normal (or preferred) power source to an emergency supply should normal voltage fail or be substantially reduced, and to retransfer it to the normal source when voltage has been restored. **Transfer switches** perform this function; they may be either manually operated or may include sensing devices which throw the switch automatically when conditions warrant. Automatic transfer switches are more frequently used. In combination with an automatic start-stop system they provide for completely unattended operation of the standby generator set.

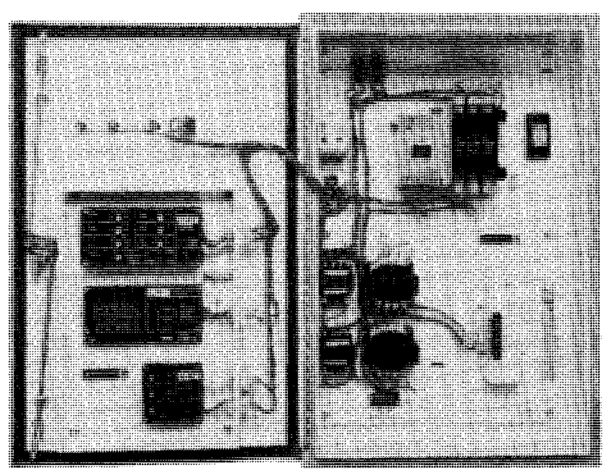
Transfer Switch Ratings

Under normal conditions, the transfer switch connects the load to the prime power source. For this reason, the contacts should be rated to handle the normal load current, even if the standby generator set is to carry only a portion of the regular load. Since the switches are usually employed in applications calling for long-sustained operation, they should be sized for continuous service. A good figure to use in determining the normal load current rating is the 15 minute demand load. Transfer switches are rated for all-class inductive loads or for non-inductive loads. For three-phase loads comprised of motors alone or of motors mixed with non-inductive loads, such as lighting or heating devices, the all-class load switch should be used. In applications where the motor and lighting loads are separate, thus requiring one three-pole switch for the motor load and a two-pole switch for the lighting load, it is possible to use a lower cost non-inductive transfer switch for the lighting load. For voltages above 600 volts, oil-type transfer switches are required.

For reasons of maximum standby system reliability, cables carrying power from the prime source and those from the standby generator set are never run in the same conduits or housings, with the single exception of the transfer switch cabinet. By observing this precaution, damage to leads carrying power from one source will not simultaneously damage leads from the other source, making it inoperable also.

Automatic Transfer Switches

The **automatic transfer switch** includes voltage-sensing supervisory relays to trip the switch when the voltage of the incoming prime source falls below a specified value, normally 70 percent of rated voltage. Figure 26 shows a typical transfer switch assembly. There are some applications where 70 percent voltage is intolerable. Close differential relays are available which actuate the switch at voltages as high as 90 percent of normal.



Automatic Transfer Switch
Figure 26

All electrical power systems are subject to transient outages of duration less than one or two seconds. It is desirable to prevent the transfer switch from actuating on these momentary interruptions, especially if the installation is equipped with an automatic start-stop system, since the transient failures will cause the generator set cranking motors to start. Transfer switches with time delay relays set for a delay of 1 to 3 seconds can eliminate unnecessary actuation of the switch.

Time delays can also be provided to prevent the transfer switch from reconnecting the load to the normal power source until its stability is certain. This feature prevents having to repeat the transfer operation should the normal power source be restored only momentarily or intermittently for a period of time. Another reason for using a delay on retransfer is that an engine, once started, should be allowed to run until it has reached operating temperature to eliminate moisture condensation. The retransfer delay can be selected to provide the necessary warmup period.

Another convenient addition to the automatic transfer switch is a test switch, which allows the operator to simulate a prime-source failure for purposes of equipment testing. In most emergency standby systems, the addition of a battery charger is required to keep cranking batteries fully charged. Some transfer switches are available with a built-in trickle charger.

GROUND FAULT PROTECTION

Recent codes and regulations are requiring that larger prime power and standby generator sets be capable of operating into electrical distribution systems having ground fault detection or protection equipment. Available systems provide protection from arcing faults in wiring and distribution panels on the load side of the generator circuit breaker. Generally the fault system consists of a sensing device that opens the circuit breaker by the shunt trip when some predetermined value of ground return (not neutral return) current exists. There are two general types of sensing devices. One measures the amount of current returning to generator (or transformer) neutral by way of the earth ground connection or ground strap. This system is commonly called "ground strap detection," and is readily adaptable to existing distribution systems.

The other system is called "zero sequence" or "phase-neutral conductor detection". It works on the principle that instantaneous summation of currents in the three lines and the neutral lead must be zero. In event of a fault to ground somewhere beyond the circuit breaker, zero summation no longer exists at the detection device. The resulting induced current in the detection transformer triggers the shunt trip on the circuit breaker.

When a ground fault protection system is used, or contemplated, generator frame and neutral grounding become very important. Only one path from ground to generator neutral assures maximum protection capability of either type fault detection system.

AUTOMATIC START-STOP SYSTEMS

As mentioned above, equipment is available for use in standby systems to automatically start the generator set and transfer the load to it when normal power is interrupted. The latter fuction is provided by an automatic transfer switch, which in this case should be equipped with an auxiliary or pilot contact to actuate the automatic cranking control panel. The cranking control devices start the cranking motor and keep it in operation until sensing devices indicate that the engine has started. Provision is usually included to shut down the generator set upon command from the automatic transfer switch after normal power has been restored. With this type of system, standby generator set operation may be completely unattended except for periods of routine maintenance and testing. For successful operation of an automatic start-stop system, the transfer switch should include both start and retransfer delay relays as well as a test switch. Automatic start-stop systems may also include paralleling and load sharing.

REGENERATIVE POWER — PARASITIC LOADS

On-line electric motors can deliver power to the line if driven above their synchronous speed. A squirrel cage motor, for example, can produce almost as much power working as a generator as it absorbs when running as a motor. This is called regeneration and is cause for caution when a generator set is supplying power to highly cyclic motor loads such as elevators, hoists, or conveyors. If motor load can deliver regenerative power, some load may be necessary to absorb this power. It may be possible to overspeed the driving engine if it is the only power absorbing unit on the line. In this instance, the friction horsepower of the engine and the losses in the generator are the only restraining effort. Safety considerations may require that a parasitic load be kept on any system where regenerative power can possibly exceed the engine friction horsepower.

SOLID-STATE (SCR) CONTROLLED LOADS

Solid-state electronic switching devices are extensively used in commercial applications ranging from lamp dimmers to DC voltage level conversion. This entire group of devices is generally called "SCR drives". Benefits gained by solid-state rectifier-type devices are accompanied by certain penalties which affect all power sources. The undesirable effects are most evident when the power source is of limited capacity, such as a generator set. Inherent operating characteristics of the SCR control system can result in problems with the controlled equipment, with instruments or monitoring devices, with other loads connected to the same generator set, or possibly with the generator set. Since these indications seldom appear when these items are powered from an unlimited source (utility), the generator set is held at fault. Some controlled equipment uses a bank of capacitors to help the operating power factor on the utility source. If the same system is powered from a generator set, the capacitors may supply enough leading power factor current to overexcite the generator, making the automatic voltage regulator ineffective. Possible difficulty can be minimized if the SCR drive supplier is advised that his equipment will be operating from a limited source.

V. ELECTRICAL TABLES

TABLE 1
ELECTRICAL FORMULAE

To Obtain	Alternating Current — Single-Phase	Alternating Current — Three-Phase	Direct Current	
Kilowatts	$\frac{V \times I \times P.F.}{1000}$	$\frac{1.732 \times V \times I \times P.F.}{1000}$	$\frac{V \times I}{1000}$	(Eq. 19)
KV·A	$\frac{V \times I}{1000}$	$\frac{1.732 \times V \times I}{1000}$		(Eq. 20)
Horsepower required when KW known (Generator)	$\frac{KW}{.746 \times EFF. (Gen.)}$	$\frac{KW}{.746 \times EFF. (Gen.)}$	$\frac{KW}{.746 \times EFF. (Gen.)}$	(Eq. 21)
KW input when HP known (Motor)	$\frac{HP \times .746}{EFF. (Mot.)}$	$\frac{HP \times .746}{EFF. (Mot.)}$	$\frac{HP \times .746}{EFF. (Mot.)}$	(Eq. 22)
Amperes when HP known	$\frac{HP \times 746}{V \times P.F. \times EFF.}$	$\frac{HP \times 746}{1.732 \times V \times EFF. \times P.F.}$	$\frac{HP \times 746}{V \times EFF.}$	(Eq. 23)
Amperes when KW known	$\frac{KW \times 1000}{V \times P.F.}$	$\frac{KW \times 1000}{1.732 \times V \times P.F.}$	$\frac{KW \times 1000}{V}$	(Eq. 24)
Amperes when KV·A known	$\frac{KV{\cdot}A \times 1000}{V}$	$\frac{KV{\cdot}A \times 1000}{1.732 \times V}$		(Eq. 25)
Frequency (c.p.s.)	$\frac{Poles \times RPM}{120}$	$\frac{Poles \times RPM}{120}$		(Eq. 26)
Reactive KV·A (KVAR)	$\frac{V \times I \times \sqrt{1-(P.F.)^2}}{1000}$	$\frac{1.732 \times V \times I \times \sqrt{1-(P.F.)^2}}{1000}$		(Eq. 27)
% Voltage Regulation	$\frac{100\,(V_{NL} - V_{FL})}{V_{FL}}$	$\frac{100\,(V_{NL} - V_{FL})}{V_{FL}}$	$\frac{100\,(V_{NL} - V_{FL})}{V_{FL}}$	(Eq. 28)

The following abbreviations are used in the table:

- V = voltage in volts
- I = current in amperes
- KW = power in kilowatts (actual power)
- KV•A = kilovolt-amperes (apparent power)
- HP = horsepower
- RPM = revolutions per minute
- KVAR = reactive kilovolt-amperes
- EFF. = efficiency as a decimal factor
- NL = no load
- FL = full load
- P.F. = power factor

NOTE: DC KW = DC KV•A

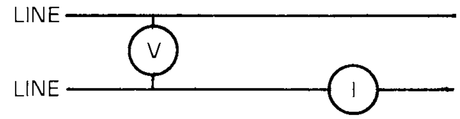
Because the basic units of electrical quantities are often inconveniently large or small, prefixes are often added to the terms which denote those units. The prefixes have the effect of multiplying or dividing the quantity by some factor, usually one thousand or one million. "kilo—" is used, for instance, to express a multiplication of one thousand. A kilovolt (kV) is therefore 1000 volts. A milliampere (mA) is one thousandth of an ampere. The commonly-used prefixes, their multiplying factors and their abbreviations are tabulated below:

Prefix	Factor	Symbol
kilo—	x 1000	k
mega—	x 1,000,000	M
milli—	÷ 1000	m
micro—	÷ 1,000,000	μ

TABLE 2
KV·A OF AC CIRCUITS

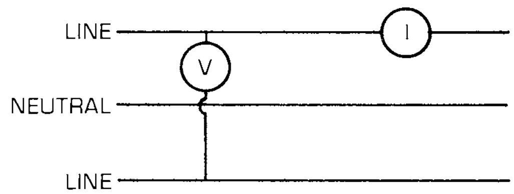
Single-Phase, Two-Wire

$$KV{\cdot}A = \frac{V \times I}{1000}$$



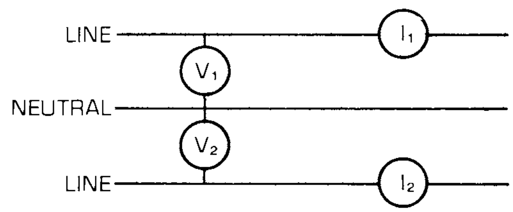
Single-Phase, Three-Wire—Balanced

$$KV{\cdot}A = \frac{V \times I}{1000}$$



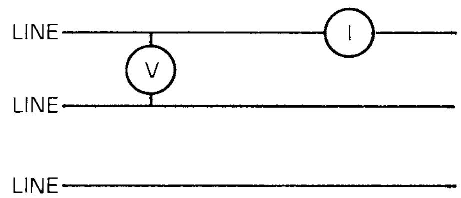
Single-Phase, Three-Wire—Unbalanced

$$KV{\cdot}A = \frac{(V_1 \times I_1) + (V_2 \times I_2)}{1000}$$



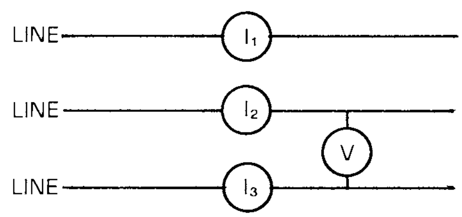
Three-Phase, Three-Wire—Balanced

$$KV{\cdot}A = \frac{1.732 \times V \times I}{1000}$$



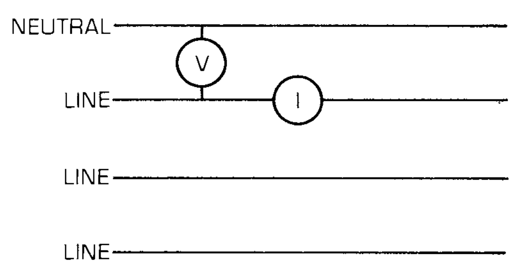
Three-Phase, Three-Wire—Unbalanced

$$KV{\cdot}A = \frac{1.732 \times V \times \left(\frac{I_1 + I_2 + I_3}{3}\right)}{1000}$$



Three-Phase, Four-Wire—Balanced

$$KV{\cdot}A = \frac{3 \times V \times I}{1000}$$



Three-Phase, Four-Wire—Unbalanced

$$KV{\cdot}A = \frac{3 \times V \times \left(\frac{I_1 + I_2 + I_3}{3}\right)}{1000}$$

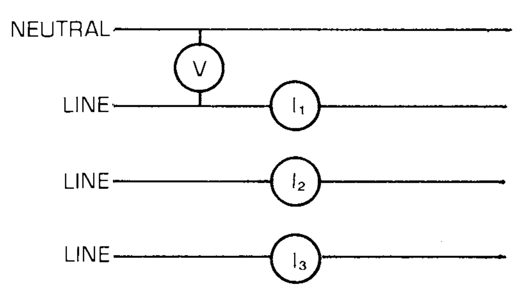


TABLE 3
COPPER WIRE CHARACTERISTICS

Wire Size AWG (B & S)	Diam. in Mils	Circular mil Area	Ohms per 1000 ft. 25° C (77° F)	Diam. in mm	Nearest British SWG No.
1	289.3	83690	.1264	7.348	1
2	257.6	66370	.1593	6.544	3
3	229.4	52640	.2009	5.827	4
4	204.3	41740	.2533	5.189	5
5	181.9	33100	.3195	4.621	7
6	162.0	26250	.4028	4.115	8
7	144.3	20820	.5080	3.665	9
8	128.5	16510	.6405	3.264	10
9	114.4	13090	.8077	2.906	11
10	101.9	10380	1.018	2.588	12
11	90.7	8234	1.284	2.305	13
12	80.8	6530	1.619	2.053	14
13	72.0	5178	2.042	1.828	15
14	64.1	4107	2.575	1.628	16
15	57.1	3257	3.247	1.450	17
16	50.8	2583	4.094	1.291	18
17	45.3	2048	5.163	1.150	18
18	40.3	1624	6.510	1.024	19
19	35.9	1288	8.210	.912	20
20	32.0	1022	10.35	.812	21

TABLE 4
SINGLE-PHASE AC MOTORS
FULL LOAD CURRENTS IN AMPERES

HP	115 V	208 V	230 V	440 V
1/4	5.8	3.2	2.9	
1/3	7.2	4.0	3.6	
1/2	9.8	5.4	4.9	
3/4	13.8	7.6	6.9	
1	16	8.8	8	
1 1/2	20	11	10	
2	24	13.2	12	
3	34	19	17	
5	56	31	28	
7 1/2	80	44	40	21
10	100	55	50	26

TABLE 5
THREE-PHASE AC MOTORS—80% POWER FACTOR
FULL LOAD CURRENT IN AMPERES
INDUCTION-TYPE, SQUIRREL CAGE AND WOUND ROTOR

HP	110 V	208 V	220 V	440 V	550 V	2300 V
½	4	2.1	2	1	.8	
¾	5.6	3.0	2.8	1.4	1.1	
1	7	3.7	3.5	1.8	1.4	
1½	10	5.3	5	2.5	2.0	
2	13	6.9	6.5	3.3	2.6	
3		9.5	9	4.5	4	
5		16	15	7.5	6	
7½		23	22	11	9	
10		29	27	14	11	
15		43	40	20	16	
20		55	52	26	21	
25		68	64	32	26	7
30		83	78	39	31	8.5
40		110	104	52	41	10.5
50		133	125	63	50	13
60		159	150	75	60	16
75		198	185	93	74	19
100		262	246	123	98	25
125		330	310	155	124	31
150		380	360	180	144	37
200		510	480	240	192	48
250		697	657	328	262	65.7
300		837	790	394.5	315	78.8
350		976	922	461	368	92.2
400		1114	1051	526	421	105.2
450		1254	1192	592	473	118.3
500		1393	1317	657	526	130
600		1672	1578	789	632	157
700		1950	1842	921	737	184
800		2220	2103	1051	842	210
900		2504	2365	1194	947	233
1000		2789	2639	1316	1050	265

TABLE 6
DIRECT CURRENT MOTORS
FULL LOAD CURRENT IN AMPERES

HP	115 V	230 V	550 V
¼	3	1.5	
⅓	3.8	1.9	
½	5.4	2.7	
¾	7.4	3.7	1.6
1	9.6	4.8	2.0
1½	13.2	6.6	2.7
2	17	8.5	3.6
3	25	12.5	5.2
5	40	20	8.3
7½	58	29	12
10	76	38	16
15	112	56	23
20	148	74	31
25	184	92	38
30	220	110	46
40	292	146	61
50	360	180	75
60	430	215	90
75	536	268	111
100		355	148
125		443	184
150		534	220
200		712	295

TABLE 7
CONDUIT SIZES FOR CONDUCTORS

Size AWG or MCM	Number of Conductors in One Conduit or Tubing✻								
	1	2	3	4	5	6	7	8	9
18	½	½	½	½	½	½	½	¾	¾
16	½	½	½	½	½	½	¾	¾	¾
14	½	½	½	½	¾	¾	1	1	1
12	½	½	½	¾	¾	1	1	1	1¼
10	½	¾	¾	¾	1	1	1	1¼	1¼
8	½	¾	¾	1	1¼	1¼	1¼	1½	1½
6	½	1	1	1¼	1½	1½	2	2	2
4	½	1¼	†1¼	1½	1½	2	2	2	2½
3	¾	1¼	1¼	1½	2	2	2	2½	2½
2	¾	1¼	1¼	2	2	2	2½	2½	2½
1	¾	1¼	1½	2	2½	2½	2½	3	3
0	¾	1½	2	2	2½	2½	3	3	3
00	1	2	2	2½	2½	3	3	3	3½
000	1	2	2	2½	3	3	3	3½	3½
0000	1¼	2	2½	3	3	3	3½	3½	4
250	1¼	2½	2½	3	3	3½	4	4	5
300	1¼	2½	2½	3	3½	4	4	5	5
350	1¼	3	3	3½	3½	4	5	5	5
400	1½	3	3	3½	4	4	5	5	5
500	1½	3	3	3½	4	5	5	5	6
600	2	3½	3½	4	5	5	6	6	6
700	2	3½	3½	5	5	5	6	6	
750	2	3½	3½	5	5	6	6	6	
800	2	3½	4	5	5	6	6		
900	2	4	4	5	6	6	6		
1000	2	4	4	5	6	6			
1250	2½	5	5	6	6				
1500	3	5	5	6					
1750	3	5	6	6					
2000	3	6	6						

† Where a service run of conduit or metallic tubing does not exceed 50 feet (15.3 m) in length and does not contain more than the equivalent of two quarter bends from end to end, two No. 4 insulated and one No. 4 bare conductors may be installed in 1-inch (25.4 mm) conduit or tubing.

✻ Rubber covered: Types RF-2, RFH-2, R, RH, RW, RH-RW, RU, RUH, RUW
Thermoplastic: Types TF, T, and TW

TABLE 8
ALLOWABLE CURRENT-CARRYING CAPACITIES OF INSULATED COPPER CONDUCTORS*

	60°C	75°C	85°C	110°C	125°C	200°
	TYPES OF INSULATION					
	Rubber		Paper	Asbestos		
Size, AWG or MCM	R, RW, RU, RUW 14-2 Thermo-plastic T, TW	TYPE RH, RHW	Var-Cam-Type V 90°C Thermo-plastic Asbestos-TA Asbestos-Var-Cam-AVB	Var-Cam Type AVA Type AVL	Impregnated Type A1 14-8 A1A	Type A 14-8 AA
14	15	15	25	30	30	30
12	20	20	30	35	40	40
10	30	30	40	45	50	55
8	40	45	50	60	65	70
6	55	65	70	80	85	95
4	70	85	90	105	115	120
3	80	100	105	120	130	145
2	95	115	120	135	145	165
1	110	130	140	160	170	190
0	125	150	155	190	200	225
00	145	175	185	215	230	250
000	165	200	210	245	265	285
0000	195	230	235	275	310	340
250	215	255	270	315	335	
300	240	285	300	345	380	
350	260	310	325	390	420	
400	280	335	360	420	450	
500	320	380	405	470	500	
600	355	420	455	525	545	
700	385	460	490	560	600	
750	400	475	500	580	620	
800	410	490	515	600	640	
900	435	520	555			
1000	455	545	585	680	730	
1250	495	590	645			

Correction Factors for Room Temperatures Over 30°C

C	F					
40	104	0.82	0.88	0.90	0.94	0.95
45	113	0.71	0.82	0.85	0.90	0.92
50	122	0.58	0.75	0.80	0.87	0.89

* With not more than three conductors in a raceway or cable and a room temperature of 30°C (86°F).

TABLE 9
CODE LETTERS USUALLY APPLIED TO RATINGS
OF MOTORS NORMALLY STARTED ON FULL VOLTAGE

Code Letters		F	G	H	J	K	L
Horse-Power	3-phase	15 - up	10 - 7½	5	3	2 - 1½	1
	1-phase	—	5	3	2 -1½	1 - ¾	½

TABLE 10
IDENTIFYING CODE LETTERS ON AC MOTORS*

NEMA Code Letter	Starting KV·A per HP
A	0.00- 3.14
B	3.15- 3.54
C	3.55- 3.99
D	4.00- 4.49
E	4.50- 4.99
F	5.00- 5.59
G	5.60- 6.29
H	6.30- 7.09
J	7.10- 7.99
K	8.00- 8.99
L	9.00- 9.99
M	10.00-11.19
N	11.20-12.49
P	12.50-13.99
R	14.00-15.99
S	16.00-17.99
T	18.00-19.99
U	20.00-22.39
V	22.40-

* Wound rotor motor has no code letter.
Note: Code letters apply to motors up to 200 HP.

TABLE 11
CONVERSION — HEAT AND ENERGY

1 - Kilowatt =	1.341 horsepower 44,254 foot pounds/minute 56.883 Btu/minute
1 - Kilowatt Hour =	1.341 horsepower hours 2,655,217 foot pounds 3413 Btu
1 - British Thermal Unit (Btu) =	777.97 foot pounds 1054.8 watt seconds 0.000293 kilowatt hours 0.293 watt hours 0.000393 horsepower hours
1 - Horsepower Hour =	0.7457 kilowatt hours 1,980,000 foot pounds 2545 Btu
1 - Horsepower =	0.7457 kilowatt 745.7 watts 33,000 foot pounds/minute 42,418 Btu/minute 1.0139 metric horsepower

TABLE 12
APPROXIMATE EFFICIENCES —
SQUIRREL CAGE INDUCTION MOTOR

HP	Full Load KW Required	Full Load Efficiency
1/2	0.6	68%
3/4	0.8	71%
1	1.0	75%
1 1/2	1.5	78%
2	1.9	80%
3	2.7	82%
5	4.5	83%
7 1/2	6.7	83%
10	8.8	85%
15	13.0	86%
20	16.8	89%
25	21.0	89%
30	24.9	90%
40	33.2	90%
50	41.5	90%
60	49.2	91%
75	61.5	91%
100	81.2	92%
125	101.5	92%
150	122.0	92%
200	162.5	92%
250	203.0	92%
300	243.0	92%
350	281.0	93%
400	321.0	93%
450	362.0	93%
500	401.0	93%
600	482.0	93%

NOTE: Efficiencies listed are approximate only for new or near new motors. For accurate efficiency figures check motor nameplate data with motor manufacturer or manufacturer's representative.

TABLE 13
APPROXIMATE ELECTRIC MOTOR EFFICIENCY TO USE IN CALCULATING INPUT

MOTOR SIZES	1 to 3 HP			5 to 15 HP			30 to 60 HP		
LOAD	1/2	3/4	4/4	1/2	3/4	4/4	1/2	3/4	4/4
DIRECT CURRENT									
(a) Shunt wound									
(b) Compound wound	78	82	83	80	83	85	86	87	88
(c) Series wound									
ALTERNATING CURRENT									
Single-Phase									
(a) Commutator type	65	72	75	75	78	80			
TWO-OR THREE-PHASE									
Squirrel Cage									
(a) General Purpose									
Normal starting current									
Normal starting torque	78	80	80	84.5	85	85	85	88	89
(b) Low starting current									
Normal starting torque				82	83	83	88	89	89
(c) Low starting current									
High starting torque				83	83	82	88	89	89
SLIP RING MOTOR				81	82	83	88	89	90
SYNCHRONOUS MOTOR							85	88	89

It is to be noted that efficiency of electric motors varies with speed, type and line voltage. The above percentages are therefore approximate and are intended only to assist in calculating input. Where the margin of power of generator over actual requirements is shown to be quite close, it is well to obtain true efficiency of motors from motor manufacturer.

TABLE 14
REDUCED VOLTAGE STARTERS

Type of Starter	Motor Voltage % Line Voltage	Line Current % Full Voltage Starting Current	Starting Torque % of Full Voltage Starting Torque
Full Voltage Starter	100	100	100
Auto Transformer			
80% tap	80	68	64
65% tap	65	46	42
50% tap	50	30	25
Resistor Starter			
Single Step (adjusted for motor voltage to be 80% of line voltage)	80	80	64
Reactor			
50% tap	50	50	25
45% tap	45	45	20
37.5% tap	37.5	37.5	14
Part Winding			
(low speed motors only)			
75% winding	100	75	75
50% winding	100	50	50

TABLE 15
COMPARISON OF REDUCED VOLTAGE STARTING METHODS

Characteristic	Autotransformer	Primary Resistor	Reactor	Two-Step Part Winding
Starting Line Current at Same Motor Terminal Voltage	Least	..........More than autotransformer type..........		
Starting Power Factor	Low	High*	Low	Low
Power Draw from Line During Starting	Low	..........More than autotransformer type..........		
Torque	Increases slightly with speed	Increases rapidly with ....speed...........		Increases slightly with speed
Smoothness of Acceleration	Motor momentarily disconnected from line from start to run	Smooth. Transfer made with little change in ....motor terminal voltage....		Smooth
Relative Cost	Average	Lower in small size - otherwise equal	Average	Less than others
Ease of Control	Same	Same	Same	No provision for adjustment of starting current
Maintenance	Same	Same	Same	Less than others
Line Disturbance	.......Varies with conditions and type of load.......			More than others

* Resistor starting adds considerable kW load to a generator set. Total power required includes the motor kW and the kW which is lost as heat in the resistor. The series resistors account for a higher than normal starting power factor.

TABLE 16
EFFICIENCY OF DIRECT CURRENT GENERATORS

		KW CAPACITY									
		1200 RPM				1800 RPM					
LOAD	VOLTAGE	100	200	250	300	30	40	60	75	100	150
4/4	125	90.5	90.0	90.5	92.3	87.5	86.5	89.0	90.0	89.3	90.0
	250	91.0	92.0	92.2		87.5	89.0	90.0	90.0	90.6	
3/4	125	90.0	88.3	89.2	91.3	86.5	84.0	87.0	88.5	88.0	89.5
	250	90.0	91.2	91.3		86.0	87.0	89.0	88.5	89.5	
2/4	125	88.0	85.0	86.5	89.2	84.5	80.5	85.0	87.0	85.1	88.0
	250	89.0	89.0	89.4		83.0	83.5	87.0	87.0	86.8	

Note: Efficiencies of 3-wire generators will be slightly lower than those of 250-volt generators because of losses in 3-wire parts.

TABLE 17
TYPES OF ELECTRIC MOTORS AND WHERE USED

Motor Types	Where Used
DIRECT CURRENT — Infinitely Variable Speed	
1. Shunt Wound	- General purpose (light starting loads)
2. Series Wound	- Hoists, cranes (heavy starting loads)
3. Compound Wound	- Machine tools, pumps, etc.
ALTERNATING CURRENT — Constant Speed Except Where Indicated	
Single-Phase, 2-Wire	
1. Commutator Type	- Small tools and printing presses
2. Centrifugal Switch	- Blowers, centrifugal pumps, etc.
3. Capacitor Type	- High starting torque applications
Three-Phase	
1. Squirrel Cage Induction* (has no commutator or brushes)	
a. Normal starting current, normal starting torque	- General purpose such as blowers
b. Low starting current, normal starting torque	- Machine tools, textile machinery, attrition mills, feed grinders
c. High starting torque, low starting current	- Compressors, conveyors
2. Synchronous (has two collector rings)	- General purpose, especially where isochronous speed is desirable. Seldom used under 40 HP. In larger sizes sometimes used as a means of improving a lagging power factor.
3. Wound Rotor* (has three collector rings)	- Car pullers, hoists, hammer mills, winches, presses, crushers where variable speed is required.

*Modern practice is often the use of a squirrel cage induction motor with thyristor control to provide variable speed. The thyristor is a silicon controlled rectifier (SCR) with which the power input to a motor can be controlled.

TABLE 18
POWER FACTOR OF TYPICAL AC LOADS

UNITY (OR NEAR UNITY) POWER FACTOR		LAGGING POWER FACTOR		LEADING POWER FACTOR
Load	**Approximate Power Factor**	**Load**	**Approximate Power Factor**	**Load**
Incandescent Lamps (Power factor of lamp circuits operating off step-down transformers will be somewhat below unity)	1.0	Induction Motors (rated load & speed)		Synchronous Motors are designed in standard ratings at unity, 0.9 and 0.8 leading power factor.
		Split phase below 1 HP	.55 to .75	
		Split phase 1 to 10 HP	.75 to .85	
		Polyphase, Squirrel Cage		
		High speed 1 to 10 HP	.75 to .90	
Fluorescent Lamps (With built-in capacitor)	.95 to .97	High speed 10 HP and larger	.85 to .92	Synchronous Condensers-nearly zero leading power factor. (Output practically all leading reactive kV·A)
		Low speed	.70 to .85	
Resistor Heating Apparatus	1.0			
		Wound Rotor	.80 to .90	
Synchronous Motors (Operate at leading power factor at part loads; also built for leading power factor operation)	1.0	Groups of Induction Motors	.50 to .90	
		Welders		Capacitors-zero leading power factor (Output practically all leading reactive kV·A)
		Motor generator type	.50 to .60	
		Transformer type	.50 to .70	
Rotary Converters	1.0			
		Arc Furnaces	.80 to .90	
		Induction Furnaces	.60 to .70	

VI. INDEX OF TECHNICAL TERMS

The terms below are described or discussed on the indicated page in the text or defined here.

Across-the-line starting
    Refers to starting an electric motor at the available supply voltage without the use of voltage reduction transformers.
Actual load
    Sometimes specified to indicate the actual on line load at any given time. Usually only a fraction of the connected load.
Actual power, p. 9
Alternating current (AC), p. 5
Ammeter, p. 16
Ampere (A), p. 2
Apparent power, p. 9
Armature, p. 11
Auto-compensator
    Another name for an autotransformer used to reduce the applied starting voltage of an electric motor.
Automatic start-stop system, p. 23
Automatic transfer switch, p. 22
Autotransformer, p. 11
Available current
    The maximum current which a source (generator) can supply to the terminals of the equipment being supplied. Clarity requires that the value be identified as RMS, symmetrical RMS, asymmetrical RMS or peak.

Battery, p. 11
Breakdown voltage, p. 3

Capacitance, p. 6
Capacitive reactance, p. 7
Capacitor, p. 6
Circuit, p. 3
Circuit breaker, p. 21
Collector ring, p. 12
Commutator, p. 14
Conductor, p. 3
Connected load
    Usually listed in specifications as "Total Connected Load". Refers to the total hp, kW, or KV·A connected to a system.
Current, p. 2
Current transformer, p. 16
Cycle, p. 5
Cycles per second—see hertz
Cyclic deviation angle
    Term applies to large, slow speed engines directly driving generators. Value is determined from engine cyclic irregularity and is measured in electrical degrees. Usual limit is 2.5 degrees. SR 4, SRCR generator sets show less that 1.0 degree.

Delta connection, p. 12
Direct current (DC), p. 5
Direct current generator, p. 14

Electromagnet, p. 8
Electromechanical generator, p. 11
Electromotive force (EMF), p. 2

Field winding, p. 11
Filament, p. 15
Fluorescent lamp, p. 15
Frequency, p. 5
Full-voltage starting
    Another term for across-the-line starting.

Generator, p. 14

Hertz, p. 5

Impedance, p. 9
Incandescent lamp, p. 15
Inductance, p. 8
Induction motor, p. 15
Inductive reactance, p. 9
Inductor, p. 8
Inherent regulation
    Value is 20% to 40% on most generators and is determined as follows: With fixed excitation, at full voltage, a 100% load is removed. The resulting no load voltage determines the inherent regulation. If 460 volts at full load, 560 volts at no load, the inherent regulation is $100 \div 460 =$ 22%.
Insulator, p. 3

Kilovolt—see volt
Kilowatt—see watt
KV·A, p. 18
KVAR, p. 10

Lagging phase, p. 6
Lagging power factor, p. 9
Leading phase, p. 6
Leading power factor, p. 9
Load, p. 3
Load factor
    The mathematical ratio of the actual load divided by the connected load.

Motor, p. 15
Motor-generator set
    A generator, AC or DC, driven by an electric motor. Typical usage includes arc welders, frequency changers, battery chargers, and precise frequency voltage supplies.

Neutral, p. 12

Ohm, p. 3
Ohm's law, p. 3

One Coil, p. 12, 14
Oscilloscope, p. 16

Parallel circuit, p. 4
Part-winding starter (motor)
  A system of using two or three parallel coil windings in large electric motors. Windings are sequentially connected to the line to minimize current inrush yet provide accelerating torque for the motor and its load.
Peak-to-peak voltage, p. 6
Peak voltage, p. 6
Phase (∅), p. 6
Phase sequence, p. 17
Potential difference, p. 2
Potential transformer, p. 16
Power, p. 4
Power factor, p. 9
Primary (transformer), p. 10
Primary reactor starter (motor)
  An iron core coil inserted in the line leads of electric motors to reduce starting voltage and current inrush.
Primary resistor starter (motor)
  A variable resistor (usually carbon discs) inserted in the line leads of electric motors to reduce starting voltage and current inrush.

Reactance, p. 6,
Reactive volt-ampere, p. 10
Rectifier, p. 12
Reduced-voltage starting
  Makes use of an autotransformer, primary reactor starter, or primary resistor starter to lower the starting voltage.
Resistance, p. 3
Resistor, p. 3
RKVA, p. 10
RMS, p. 6

Secondary (transformer), p. 10
Semiconductor, p. 3
Series circuit, p. 3
Short circuit ratio
  Figure gives some indication of generator response under suddenly applied load. Value is determined by test and is usually 0.4 to 0.8.
Silicon controlled rectifier (SCR), p. 12
Sine wave, p. 5
Single-phase AC circuit, p. 14
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Slip ring, p. 15
Slip ring motor, p. 15
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Three-phase circuit, p. 14
Three-phase generator, p. 12
Transfer switch, p. 22
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Unity power factor, p. 9

Volt (V), p. 2
Voltage, p. 2
Voltage regulator, p. 12
Voltmeter, p. 15

Watt, p. 4
Watt-hour, p. 5
Watt-hour meter
  A recording device that totals the average power (kW) passing through it in a period of time. The reading is kilowatt hours. 10 kWh means 10 kilowatts for a one hour period, or one kilowatt for ten hours, or any product of power and time that equals ten.
Wattmeter, p. 17
Waveform, p. 5
Wound-rotor motor, p. 15
Wye connection, p. 12

X/R ratio
  This ratio is used in calculations of circuit breaker requirements. The ratio determines the time in which an asymmetrical current becomes symmetrical. Most generators have a figure of 6 to 10.

Y connection—see wye connection

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