A SunCam online continuing education course

Electrical Power Distribution Part 1
Fundamentals for Every Engineer

by

Brian Hinkle, PE

Table of Contents

Learning Objectives

This continuing education course is intended to provide training and education about the following topics:

1. Basic components in an AC electrical power distribution system
2. Measured values related to electrical power distribution (voltage, current, power, power factor and energy)
3. Electrical energy charges and billing
4. Electrical safety

Electrical Power Distribution Systems

A simplified AC electrical power distribution system consists of an electric generation source, transformers to change voltages, conductors, and switchgear for protection and control. The system should be designed to safely generate electrical power and safely transport that power to its point of use.

A traditional utility generator converts non-electrical energy to electrical energy. There are three major categories of energy sources for utility electricity generation.

1. fossil fuels (coal, natural gas, and petroleum)
2. nuclear energy
3. renewable energy sources (solar, wind, water)

The majority of prime power generation by electric utilities in the USA is from fossil fuels and nuclear power. According to the US Energy Information Administration, the breakdown of utility electricity generation fuel sources in 2019 is shown in Table 1.

Table 1: Electric Utility Generation Power Fuels 2019 - Source: US Energy Information Administration

Fuel Source	**Percentage**
Natural Gas	38%
Coal	23%
Nuclear	20%
Renewables	18%
Petroleum	1%

Utilities using fossil fuels or nuclear fuel typically generate electric power at 5kV – 34.5kV. A generator step-up transformer (GSU) at the generating station raises the voltage to transmission levels between 69kV and 765kV. Near the location of power utilization there will be one or more step-down transformers that will lower the voltage to a distribution level (15kV – 34.5kV) and utilization level (120V – 5kV). These connections are shown in Figure 1.

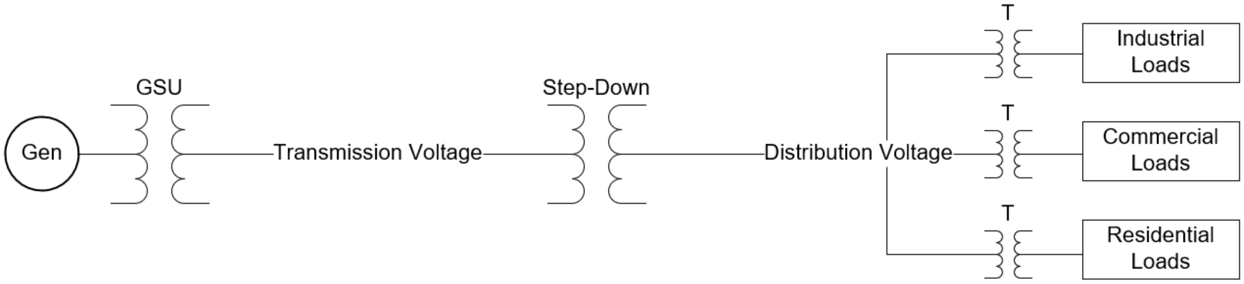

Figure 1: AC Electrical generation, transmission, and distribution

Measurements and Values

The discussion of electrical power systems requires an understanding of the measurements related to these systems. This includes the associate measured value and the units of measure.

Volts, Amps and Ohms

An electrical power system requires a source of potential energy that can be released when an electrical circuit is completed between the terminals of this source. Electrical potential energy is measured in volts and is like gravitational potential energy in a mechanical system. Examples of electrical energy sources are generators that converts rotating mechanical energy into electrical potential energy, a battery system that converts chemical energy into electrical energy, or photovoltaic cells that convert solar energy into electrical energy.

The unit of measure for electrical potential energy is volts and is abbreviated by a “V”. It is also represented by the letter “V” in equations. Common prefixes are millivolt used in electronic circuits and kilovolt used in power circuits.

Millivolt (mV)	0.001 V
Volt (V)	1 V
Kilovolt (kV)	1,000 V

The flow of electricity is measured in amperes or amps. It is abbreviated as “A” and it is represented by the letter “I” in equations. Common prefixes are milliamp used in electronic circuits and kiloamps used in electrical power circuits.

Milliamp (mA)	0.001 A
Amp (A)	1 A
Kiloamp (kA)	1000 A

An elementary circuit is shown in Figure 2. This shows a voltage source connected to a load with a switch that controls whether the circuit is completed, allowing electricity to flow through the circuit. With the open switch, this is considered an “open circuit”.

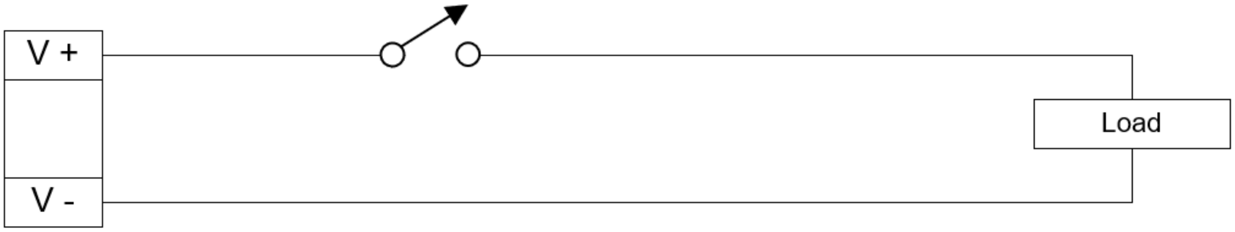

Figure 2: Electrical Circuit

The measurement of an electrical load is the characteristic called impedance. Impedance is measured in ohms. The Greek letter omega (Ω) is used for the designation of ohms. Impedance is represented by the letter “Z” in equations.

The impedance of a load is composed of three possible components. They are resistance (R), inductive reactance (X_L), and capacitive reactance (X_C). To simplify our discussion at this point, we will consider loads that are purely resistive and do not contain any inductive reactance or capacitive reactance and "R" will be used to represent the load resistance.

With the switch in the open position, there is voltage potential, but there is no electrical current flowing. When the switch is closed as shown in Figure 3, there is a complete path from the positive side of the voltage source, through wires to the load and through the wires that return to the negative side of the voltage source.

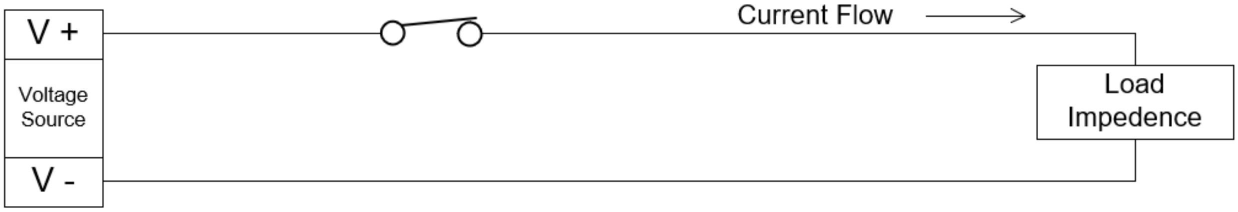

Figure 3: Closed Electrical Circuit

The relationship between voltage and current for a resistive load is described by Ohm's Law which states that the current that flows between two points is directly proportional to the voltage across the two points. This is shown in (1) where voltage (V) is measured in volts, current (I) is measured in amps and resistance (R) is measured in ohms.

$$V = IR \tag{1}$$

The equation can be rearranged to solve for the magnitude of current as shown in (2).

$$I = V/R \tag{2}$$

DC and AC Systems

Voltage sources can be direct current (DC) or alternating current (AC). In a direct current (DC) system, the voltage source is essentially constant over time. With a constant load (R) the current will also be constant over time.

Example 1
Using a 120Vdc voltage source and a 10 Ω load. The current can be calculated using (2).

I = V / R
I = 120 / 10 = 12 amps

This is shown graphically in Figure 4.

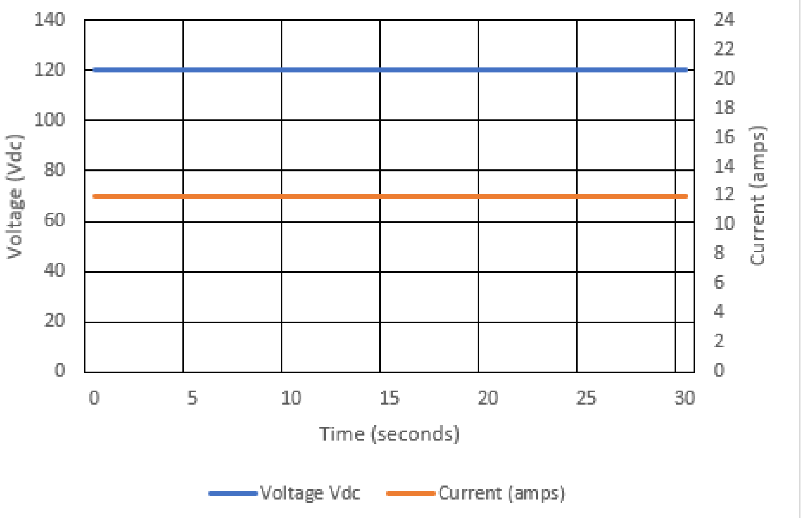

Figure 4: Graph of DC voltage and current

In an alternating current (AC) system, the voltage source varies over time following a sinusoidal waveform as shown in Figure 5.

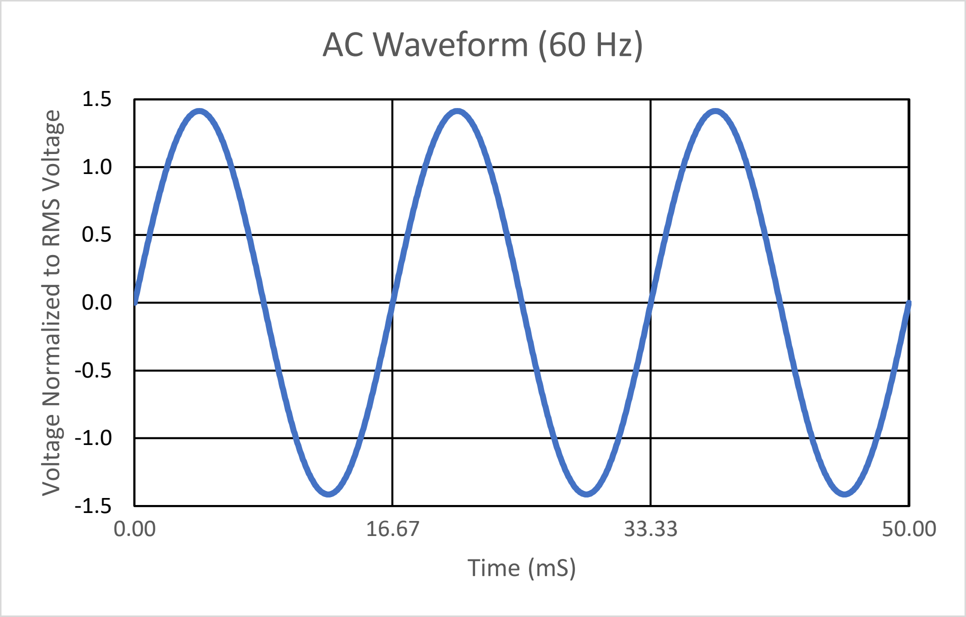

Figure 5: AC Voltage Waveform

The instantaneous value of the voltage is given by (3), where ω is the angular frequency and "t" is time. The key take away is that the voltage in an AC system is constantly varying, as compared to the voltage in a DC system which is constant. The standard frequency for voltage in the United States in 60 Hz (cycles/second).

$$V = Vmax * Sin(\omega t) \qquad (3)$$

Since the magnitude of the voltage is constantly changing, how can we use Ohm's Law to calculate the current in an AC system? For our discussion in this course, we will consider steady-state conditions where the voltage consistently follows the sinusoidal waveform with consistent peak values. For an AC system in a steady state, we use the RMS values for voltage and current rather than the instantaneous values.

RMS stands for root-mean-squared. The RMS value of a sinusoidal waveform is 0.707 times the peak of the waveform. Figure 5 shows a sinusoidal waveform with and RMS value of 1 and a peak value of 1.41.

Vrms = 0.707 * V peak
Vpeak = Vrms / 0.707 = Vrms * 1.41

You do not need to know how the RMS value is calculated, you just need to know that the RMS values of a sinusoidal voltage and current waveform are values that provide the same heating effect of an equivalent DC system. This allows us to use the RMS values from an AC system in the equations from Ohm's Law. When measuring AC voltage and current, meters that measure RMS values should be used. When dealing with AC systems, voltage and current values are assumed to be RMS values unless specifically identified as peak values.

Example 2
An AC system with 120VAC rms and a 10 Ω load. The current can be calculated using (2).

I = V / R
I = 120 / 10 = 12 amps

This is shown graphically in Figure 6. The voltage has an RMS value of 120V and a peak value of 170V.

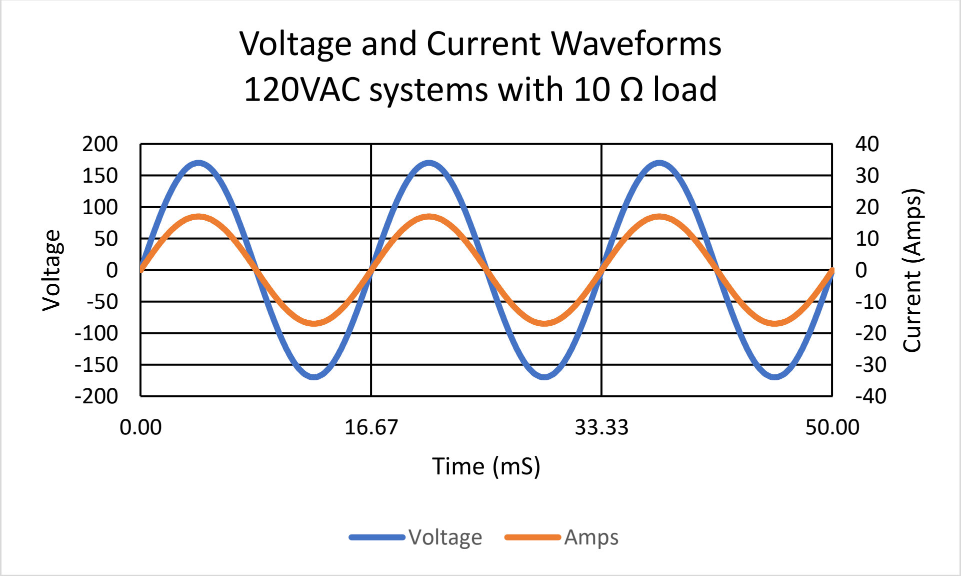

Figure 6: Voltage and Current waveforms for Example 2

Electrical Power

Electrical power is measured in watts. It is abbreviated with a “W” and is represented in equations by the letter “P”. Common prefixes are milliwatt used in electronic circuits and kilowatt or megawatt used in electrical power circuits.

Milliwatt (mW)	0.001 W
Watt (W)	1 W
Kilowatt (KW)	1,000 W
Megawatt (MW)	1,000,000 W

Power (watts) in a resistive electrical circuit is calculated using equation 4 when voltage is measured in volts and current is measured in amps.

$$P = V * I \qquad (4)$$

Substituting (1) for “V” gives us (5).

$$P = I^2 * R \qquad (5)$$

Example 3: For an AC circuit with 120 volts and a 10-ohm resistive load, what is the power delivered to the load?

From example 2 we know that the current in the circuit is 12 amps
P = V * I
P = 120 volts * 12 amps
P = 1,440 watts

Power Factor in AC Systems

The examples to this point have used a purely resistive load. When this is the case, the voltage and current waveforms in an AC system are synchronized as shown in Figure 6. When voltage and current are synchronized, the waveforms cross the horizontal axis and reach peaks at the same time. When there is inductance or capacitive reactance in the system, the current and voltage will be out of sync. When the voltage and current are not in sync, the amount of useful work done by the load will be different from the power calculated by (4).

If a circuit has inductive reactance, the current will lag the voltage, as shown in Figure 7. Inductance in a circuit is a result of changes in magnetic fields that occur in coils of wire in motors, transformers, and other components in the circuit.

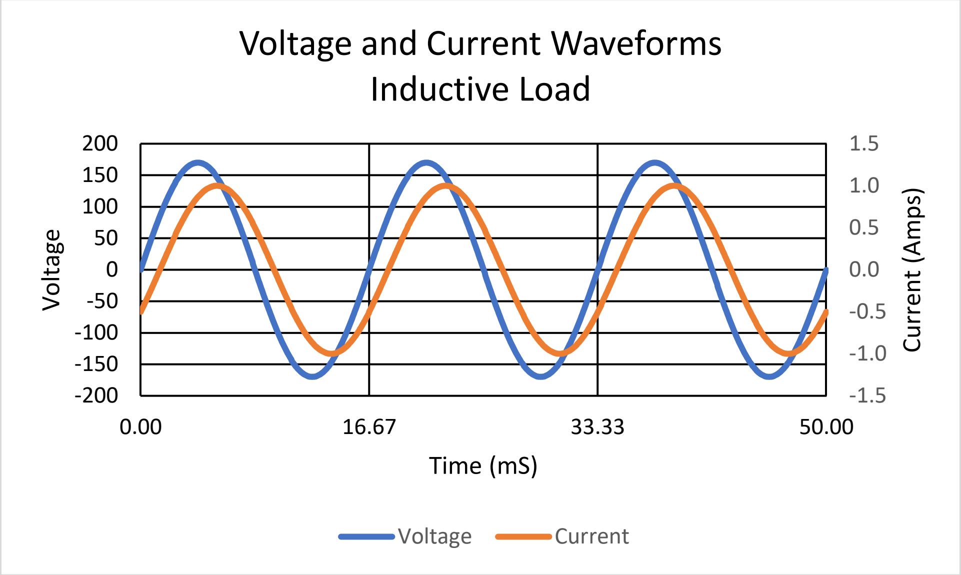

Figure 7: Voltage and Current waveforms showing current lagging the voltage

If a circuit has capacitive reactance, the current will lead the voltage as shown in Figure 8. Capacitance in a circuit is a result of charging and discharging capacitors or other charge storing elements in the circuit.

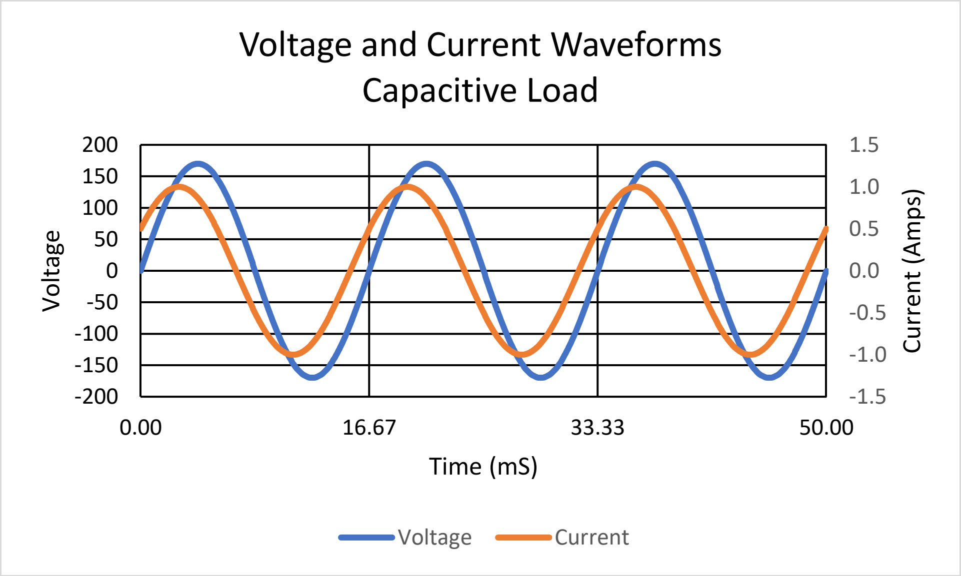

Figure 8: Voltage and Current waveforms showing current leading the voltage

In an AC system, the current that is caused by inductance or capacitance is creating magnetic fields and charging capacitors and is not doing useful work at the load. The difference between the total current and the current that does the useful work is called reactive current. There is a power measurement associated with each of these currents.

The power associated with the total current measured in the systems is called apparent power. Apparent power is the product of the voltage times the total current regardless of whether these are in sync. The unit of measure is volt-ampere, which is abbreviated VA. When used in an equation, apparent power is represented by the letter “S” and is calculated using (6).

$$S = V * I \tag{6}$$

The power associated with the work producing current is called real power. It is measured in watts as already discussed. In equations, it is represented by the letter “P”. It is calculated using (7), where φ is the angular difference between the voltage and current waveform.

$$P = V * I \cos(\varphi) \tag{7}$$

The power associated with the reactive current is called reactive power. It is measured in volt-ampere and is called volt-ampere reactive which is abbreviated VAR. It is represented by the letter “Q” and is calculated using (8).

$$Q = V * I \sin(\varphi) \tag{8}$$

Power factor is a measurement of the ratio of the working power to the apparent power. It is a dimensionless number in the range from -1 to +1.

$$\text{Power Factor} = \text{Real Power } (P) \,/\, \text{Apparent Power } (S) \tag{9}$$

If the inductive reactance in a system is greater that the capacitive reactance, the net system is inductive, and the power factor will be between 0 and 1. This is referred to as a lagging power factor because the current lags the voltage.

If the capacitive reactance is greater than the inductive reactance, the net system is capacitive, and the power factor will be between 0 and -1. This is referred to as a leading power factor because the current leads the voltage.

If there is no reactive current in a system, the power factor is 1 and referred to as “unity” or perfect power factor.

The relationship between these power values and power factor can be described graphically using the Power Triangle shown in Figure 9. The Power Triangle shows that the power factor (Real Power / Apparent Power) is the cosine of the angle between these two values. This is the reason that power factor is also referred to as Cos (φ).

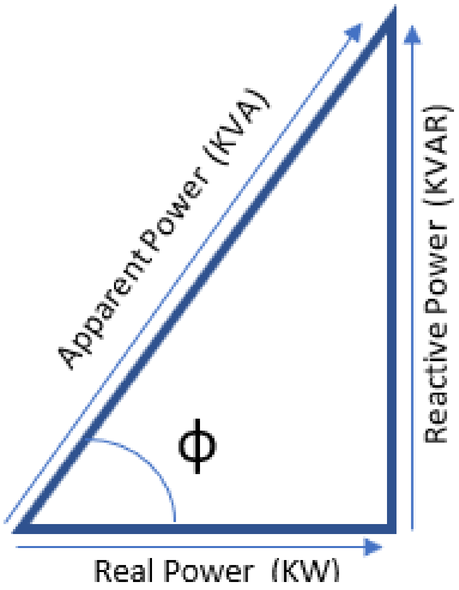

Figure 9:The Power Triangle

Power Factor – System Impact

Most industrial, commercial, and residential electrical power systems have a net inductive load and have a lagging power factor. For broader system reasons, utilities typically prefer to have customer loads that have a slightly lagging power factor. When power factor is less than unity, there is a point where the low power factor will impact system design and can have an impact on the total charges that a customer pays.

From a system design perspective, the electric utility power system must be able to carry the total current of the apparent power regardless of the true power used by the customer. Table 2 shows the total apparent power that the utility must be able to carry to deliver 1,000W of true power at various power factor levels. This shows that at 0.80 power factor they must be able to carry 25% more power than the true power consumed. At a power factor of 0.70 the utility must be able to handle current that is almost 50% more than is required for the true power used. For a system with low power factor, higher rated equipment or more cabling may be required to be installed than for a similar system with a higher power factor.

Table 2: Real Power and Apparent Power vs Power Factor

Power Factor	Power (W)	Apparent Power (VA)
1.00	1,000	1,000
0.95	1000	1,053
0.90	1,000	1,111
0.85	1,000	1,176
0.80	1,000	1,250
0.75	1,000	1,333
0.70	1,000	1,429

Single-Phase and Three-Phase AC Systems

The AC systems described so far have been single-phase systems. This means that there are two wires carrying current and only one voltage waveform. This is typical of what is used in residential, and light commercial systems. A residential system will typically have single-phase 120VAC for outlet receptacles and lighting. It may also have single-phase 240VAC for appliances that require more power such as water heaters, HVAC systems, stoves / ovens etc. Using 240VAC for the appliances that require higher power requires lower current than if they were using 120VAC.

Example 5

A Viking DECU105 electric cooktop stove has a power rating of 8,400 watts. When used on a single-phase 240VAC system, the current required can be calculated using (4).

P = V * I
8,400 watts = 240 V * I
I = 8,400 / 240
I = 35 amps

If this stove were to be wired in a single-phase 120VAC circuit, the current required is calculated by:

8,400 watts = 120V * I
I = 8,400 / 120

I = 70 amps

This shows that using higher voltage reduces the amount of current required. The wire and conduit required for the higher voltage circuit with lower current will be smaller and less expensive. Generally, as the power requirement increases, there are benefits to using a higher voltage.

Another type of AC power system is a three-phase system. A three-phase system uses 3 or 4 wires which carry 3 voltage waveforms that are offset by 120 degrees. The waveforms of the three phases are offset by 120° as shown graphically in Figure 10.

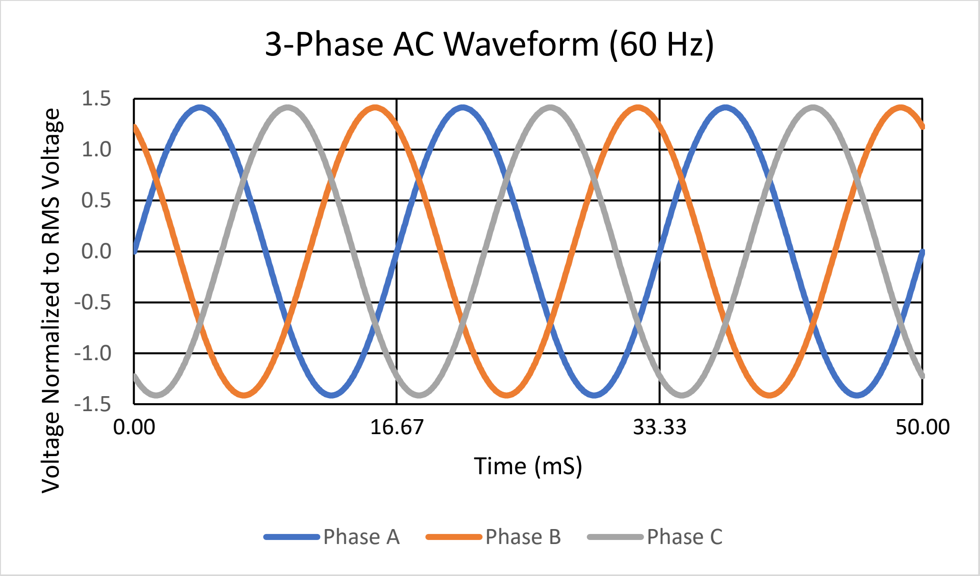

Figure 10:3-Phase Voltage Waveform, (60 Hz)

A three-phase circuit provides higher power density than a single-phase circuit with the same current. In a three-phase AC system, voltage is still measured as the RMS voltage however the calculations for power change, as shown in (10), (11), and (12). This shows that the power delivered by a three-phase system compared to a single-phase system with the same voltage and current increases by a factor of 1.73.

$$Apparent\ Power\ (S) = V_{RMS} * I * \sqrt{3} \tag{10}$$

$$Real\ Power\ (P) = V_{RMS} * I * \sqrt{3} * Cos(\varphi) \tag{11}$$

$$Reactive\ Power\ (Q) = V_{RMS} * I * \sqrt{3} * Sin\ (\varphi) \tag{12}$$

Common three-phase voltage systems for commercial or industrial applications in the USA are 208, 480, 4.16kV, and 13.8kV.

Energy Consumption and Electric Utility Billing

Electric utility billing structures and rates vary between utilities and between customer types (residential, commercial, or industrial). There may also be different rate structures available to each of these customer types.

At the most basic level, the electric utility bill will charge a customer for the energy consumed that provides real work or the real power consumed. Electric energy is the measurement of the amount of power consumed over time. This is a simple calculation of power multiplied by time as in (10).

Energy = Power * Time (10)

The unit of measure for electric energy is a watt-hour. The measurement for billing purposes is typically kilowatt-hour (KWH) or megawatt-hour (MWH). In 2019, the cost of electricity per KWH in the USA ranges between 9¢ and 23¢ with an average of 14¢.

Example 6 - Residential electric heater

For a 1,500-watt electric heater, on average, how much will it cost to run this heater for 24 hours with a utility cost of 14¢ / KWH?

Using (10)
Energy = Power * Time
Energy = 1,500 watts * 24 hours
Energy = 36,000 watt-hours

Energy (KWH) = 36,000 watt-hours / 1,000
Energy (KWH) = 36

Cost = 36 KWH * $0.14/KWH
Cost = $5.04

Large commercial or industrial customers may have charges on their bill based on other factors.

Demand charge

A demand charge is a fee based on the highest flow of power during a certain time-period. Utilities may include this type of clause because they must install equipment that is large enough to supply the customer's maximum power demand even though they do not consume that maximum power all the time. The demand charge can be based on the maximum demand each month, or it could be based on the maximum demand for the previous year. The demand charge can be based on the apparent power demand (KVA) or the real power demand (KWH).

If the demand charge is based on KVA and the customer's power factor is low, the measured peak KVA will be much larger than the measured peak KWH. Looking at Table 2, a peak load of 1,000W will have a peak KVA of 1,000KVA at unity power factor and a peak KVA of 1,429KVA at 0.70 power factor. In this case the customer is indirectly penalized for having a low power factor.

Power Factor Charges

Charges associated with power factor can be in the form of a penalty clause which charges a customer fee for having a power factor below a certain level, say 0.80. They could also have a charge for the reactive power consumed. This would be measured in KVAR-hours similar to KWH.

Other Contract Clauses

Interruptible power clauses are clauses that require a customer to reduce their power consumption below a certain point when notified by the utility. Having this in the contract will normally provide a lower price per KWH throughout the year. This type of clause allows a utility to manage the maximum system demand below a certain level in lieu of installing additional capacity.

Fuel Adjustment clauses allow a utility to adjust utility bills based on the cost of the fuel used to generate electricity. This can cause the electric bills to move in concert with the price of the fuel used by the utility. This eliminates the need for an electric utility to request rate changes from the utility commission based solely on fluctuating costs of fuel.

Time of Use clauses provide different rates based on the time of day or time of year.

Electrical Power System Safety

Everybody should have a basic understanding of electricity and be aware of the dangers associated with electrical power and how to avoid and minimize these dangers. Additionally, good engineering practices should be followed to reduce these dangers.

There are three main hazards associated with electrical power.

1. People coming in contact with energized electrical parts causing shock and burns
2. Electrical system faults which can cause fires
3. Fire or explosion caused by electric sparks as the source of ignition in an area with a flammable or explosive atmosphere

Electrical Power System Design & Safety

The National Electric Code (NEC) is one of the codes published by the National Fire Protection Association (NFPA), designated as NFPA 70. The purpose of the NEC is the practical safeguard of people and property from the hazards arising from the use of electricity. This is the code adopted by each state to establish safe practices of electrical design, installation, and inspection to protect people and equipment from electrical hazards. Within a state, city, or county there may be additional requirements established by the local authority having jurisdiction (AHJ).

Workplace Safety

Electrical hazards exist in many workplaces and pose a significant risk of injury or death to employees. According to the Electrical Safety Foundation International (ESFI), there were 166 fatal electrical injuries and 1,900 non-fatal injuries resulting in days away from work in 2019.

The Occupational Safety and Health Administration (OSHA) publishes general industry standards regarding electrical installation safety. Details can be found in Subpart S of 29 CFR Part 1910. The OSHA Act of 1970 requires employers to provide employees with a workplace that is free from recognized hazards that could cause death or serious physical harm. Because of these electrical hazards, the general rule is to only work on de-energized electrical equipment. Energized equipment is also commonly referred to as “live” or “hot” equipment. OSHA standards require that live parts must be de-energized before an employee works on or near them unless de-energizing introduces additional or increased hazards, or it is not feasible due to equipment design or operational limitations. Possible financial loss, convenience, or production concerns are not acceptable reasons to work on energized equipment.

Some ideas to increase safety and/or decrease the hazards of electrical equipment are:

- Having an effective workplace safety program for electrical and non-electrical employees.
- Prevent accidental contact with energized electrical components by use of electrical enclosures, warning / hazard signs, installing electrical equipment in locked rooms or fenced areas.
- Never work on energized equipment, using proper lockout/tagout procedures.
- Install proper barriers around electrical hazards.
- Properly maintain electrical equipment and never use electrical equipment that has been damaged, such as plugs and extension cords that have frayed or broken insulation.
- Use procedures, tools, and Personal Protective Equipment (PPE) appropriate for the work being performed.

Conductors, Insulators and Barriers

Understanding the hazards resulting from electrical system faults requires an understanding of some of the components used in electrical systems and their function.

Components and equipment in electrical power systems consist of conductors and insulators. Conductors are materials that allow electricity to flow through them. Conductors may be wires or bars made of copper or aluminum. Insulators are materials that do not allow electric current to flow through them. Common insulating materials are glass, porcelain, plastic, rubber, air, and wood. Insulators in electrical equipment have a voltage rating. The voltage rating indicates the system voltage that they are designed for. If an insulator is exposed to voltages higher than its rating, there is the possibility of an insulation failure that can create an arc, spark, or explosion. Lightning is an example of an arc that occurs when the voltage between the clouds and the ground exceeds the insulating value of air. A typical lightning flash can be several 100 million volts.

Insulators surrounding conductors are one way to prevent people from coming in contact with energized electrical parts. Another method to prevent accidental contact is the use of barriers. Barriers may come in several forms:

1. A barrier made of insulating material
2. Metal barriers that are connected to ground potential
3. Locked doors or fences that prevent people from being in close proximity to energized equipment

Types of Faults

Electrical faults can be classified as an overload, short circuit, ground fault, or an arc fault. Electrical power systems should be designed to disconnect the source of electrical power when a fault occurs. Common protective devices are fuses and circuit breakers. The term used when a circuit breaker operates based on a protective function, is called a “trip”. When a fuse operates, it is called a “blown fuse”.

Overload

An overload occurs when the current flowing in a circuit’s normal path is higher than it is designed to carry. Electrical circuits are designed to carry a specified amount of current while keeping the temperature of the components at or below a specific point. High temperatures should be avoided because they can cause conductors to melt, can cause insulation systems to fail and can cause fires.

As the current rises higher above the circuit rating, more heat is generated, and the temperature will rise faster. For this reason, the circuit will need to be disconnected from the power source in a shorter amount of time when the overload is larger. This is called an inverse time-current relationship. As the current increases, the time to trip decreases. This is shown graphically in Figure 11 for three different time-delay settings.

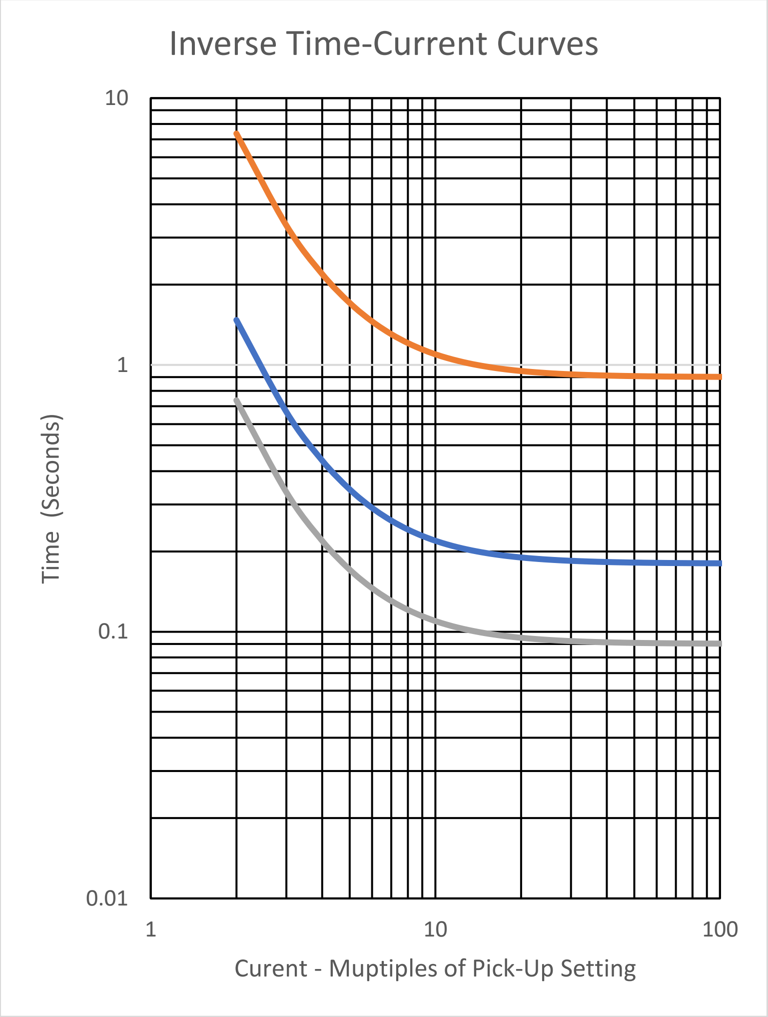

Figure 11: Inverse Tim-Current Protection Curve

Short Circuit

A phase-to-phase short circuit occurs when conductors from two different phases come in contact with each other. When this happens, the resistance between the two conductors is near zero. In this condition, the current will rapidly rise to thousands of amps. The high current produces excessive heat and has the potential to create a fire or explosion if it is not disconnected from the power source quickly. Short circuits also create mechanical stresses on the equipment due to high magnetic forces created by the high current. Under this condition fuses or circuit breakers should open the circuit with no intentional delay. This is referred to as instantaneous protection.

Electrical distribution equipment has a short circuit rating. The short circuit rating is the fault current which equipment can be connected to without sustaining damage exceeding defined acceptance criteria. Short circuit ratings are in values of ampere interrupting capacity (AIC). These ratings are in 1,000's of amps, so the rating is typically listed as KAIC. Equipment with a higher AIC rating will have more physical support to withstand the higher mechanical stresses of high short circuit currents than equipment with a lower AIC rating.

Ground Fault

A ground fault occurs when a phase conductor unintentionally comes in contact with a normally non-current carrying conductor which has a path to ground potential. This is also called a phase-to-ground short circuit. This can occur when insulation on a conductor is broken, cracked, or worn away and the conductor comes in contact with the equipment enclosure or a person.

Arc Fault

An arc fault occurs when an electrical arc is created between two conductors due to an insulation failure or broken wire. When an arc is initiated, there is resistance in the arc that prevents the extremely high currents of a short circuit. As the arc continues, it creates heat which decreases the resistance. The current and heat continue to increase to temperatures above 30,000°F. At this temperature, insulators and conductors melt or vaporize releasing an explosion.

Protective Devices

Electrical circuits can be protected by fuses or circuit breakers. Both types of devices can provide protection for overloads and short circuits.

A fuse is an electrical component that consists of a metal strip inside a housing and is inserted in the circuit. Under normal current conditions, current flows through the fuse without impact to the circuit. Under an overload or short circuit condition, the higher current causes the metal strip to melt, opening the circuit. This is referred to a “blown fuse”. Fuses are single-use devices that must be replaced when they blow. Each fuse is designed to melt in a predetermined time under specific levels of current. The relationship between the amount of current and the time delay until it blows is called the time-current curve. To get a different time-current curve, one fuse must be replaced with a fuse of a different design.

A circuit breaker is a device designed to open and close a circuit by nonautomatic means and to open a circuit automatically on a predetermined overcurrent without damage to itself when properly applied within its ratings. When a circuit breaker opens automatically, it is referred to as a “trip”. After the circuit breaker trips due to an overload or short circuit, it can be used to close the circuit after it is determined that it is safe to do so. This contrasts with fuses, which must be replaced after blowing due to an overload or short circuit.

Circuit breakers are available in several varieties with differing features and adjustments. For a thermal-magnetic circuit breaker, protection against overloads uses heat created by the overload to cause the circuit breaker to trip, and this is called thermal protection. Protection against short-circuit faults uses the magnetic forces caused by the high short-circuit current to trip the breaker and is called magnetic protection or instantaneous protection. Circuit breakers that are designed to protect against overload and short-circuit are called thermal-mag breakers. Circuit breakers designed to protect against only short circuits are called mag-only or instantaneous-only breakers.

A nonadjustable circuit breaker is one which does not have any adjustments to alter the value of current at which it will trip, or the time required for the operation. The time-current curve of a circuit breaker is also called its trip curve. This is the type of circuit breakers found in most homes.

An adjustable circuit breaker can be set to trip at different values of current, time, or both, within a predetermined range. The settings that are available for adjustment can vary between circuit breaker types. This type of circuit breaker provides flexibility to achieve the required circuit protection.

Bringing It All Together

This course has introduced the basic components used in electrical power distribution systems from utility generation through transmission and distribution to the point of consumption.

Electrical values for voltage, current, power, power factor and energy have been explained providing the student with a foundation to participate in discussions about electrical power distribution systems and equipment.

The explanation of energy consumption, demand charges and power factor charges provide an understand of how these factors impact the life cycle costs of operating electrical power systems.

The need for electrical safety was explained along with causes of electrical hazards and protective devices that can be used to provide protection.

The overview of these topics provides engineers, managers, and system operators enough background information to participate in discussions about electrical power distribution system design, life-cycle costs, and safety.