Electrical Tech Note — 225

Biosystems & Agricultural Engineering Department
Michigan State University

Electrical Power Transmission and Distribution

Electrical power is generated at strategic locations around the country and a delivery system is needed to transport this power from the generation facilities to communities where it can be distributed to customers. An electrical transmission system like a super highway moves bulk power from the power plants to the points of distribution. Transmission systems across North America are interconnected to form a *power grid* to allow utilities to buy and sell electrical power. If a power plant is taken out of service at one utility, that utility can purchase power from another supplier who has excess capacity available. The transmission system is used to transport that bulk electrical power. *Distribution lines are used to deliver power to customers*. Distribution lines get their power from the transmission system or sometimes from local generating facilities. Distribution systems operate at lower voltages than the transmission system. Transformers are used to change the voltage. These transformers are placed in small areas within a chain-link fence with other control equipment. These facilities are called *substations*.

Transmission System: Transmission lines operate at very high voltage and are usually run overhead supported on tall poles or steel structures. A transmission line is shown in Figure 225.1. The amount of electrical power to be transported is proportional to the voltage times the current. The transmission wire size must be adequate to carry the current. Current is the quantity that limits the capacity of the transmission line. By *increasing the operating voltage of the transmission line, more electrical energy can be delivered with minimal loss of power*.

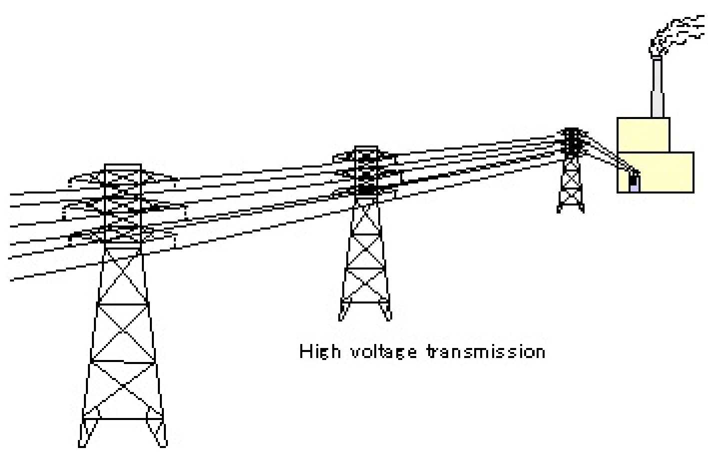

Figure 225.1 *High voltage transmission lines are necessary to transport large quantities of bulk electrical power from the power plants to points of use with minimal current.*

The following example illustrates the need for high voltage for electrical power transmission. Assume that a small community has 100 homes each drawing 50 amperes at 240 volts at the same time. The total current being drawn by the homes is 5000 amperes at 240 volts. If these homes are supplied by a single-phase distribution line operating at 7200 volts, the current flow on the distribution line to supply these homes will be 167 amperes. If power is delivered to this community by a 365,000 volt transmission line, the transmission line current required to supply the homes will only be 3.3 amperes. *It is necessary to increase the voltage of the utility electrical lines to deliver power over long distances without excessive losses*.

When electrical power is transported, losses will occur as the current flow experiences the resistance of the wires. By increasing the voltage, the same amount of power can be delivered by the line with less current and lower losses. The fact is that transmission systems must operate at high voltage in order to effectively transport electrical power long distances between power plants sometimes located in adjacent states. Most transmission lines operate as 3-phase alternating current lines. These lines have three sets of circuit conductors. Some transmission lines in North America operate at up to 765,000 volts. There are a number of direct current transmission lines operating in North America and they may operate at as high as one million volts. Direct current transmission lines have two conductors, one with a positive voltage and one with a negative voltage. *The advantage of direct current transmission over alternating current lines is lower losses*. Electrical power is produced as alternating current and used as alternating current. If direct current transmission is used, the alternating current must be rectified to direct current and than inverted back into alternating current at the points of use. Only in recent years has it become economically and technically feasible to rectify and invert bulk power at high voltage.

Above-ground transmission lines are the most common type installed with the wires supported on wood pole structures or steel structures. Since resistance of the wire will cause the wires to heat up when current flows, wires installed in the open air are cooled by the free flow of air around the wires. Wires that get hot will lengthen due to thermal expansion and will droop closer to the ground. Limiting the temperature of the line is important. *Larger quantities of electrical power can usually be transported with an overhead line than an underground line with the same wire size*.

Underground transmission lines are used, but construction costs are much higher and sometimes the environmental impact is greater than locating lines above ground. Underground transmission lines are generally limited to congested urban areas with limited space, or where the overhead lines would be an obstruction such as near an airport. Maintenance and repairs are more difficult with underground lines. Repair time on a faulted line may take days rather than hours to repair and return to service. When transmission lines are installed underground, there are three basic types of construction. The wires may be placed in a pipe filled with high pressure oil. Another type of line places the conductors in pipe that is pressurized with nitrogen. The other type of construction places high voltage insulated conductors in PVC nonmetallic pipe and embedding the pipes in a concrete casing. *Transmission lines that are installed underground are cooled by conduction to the surrounding earth which is not nearly as effective at cooling as suspending the conductors in open air*. This means the same wire size buried underground will deliver much less power than if the same wire size is installed overhead.

Concerns About Transmission Lines: One concern about overhead transmission lines is their unsightliness. Many persons do not want to look out of their homes to see big structures and overhead wires. Another concern is whether there are health effects. High voltage transmission lines produce *air ions*, *electric fields*, and *magnetic fields* in the vicinity near the lines. Direct current lines produce a larger quantity of air ions than do alternating current lines. These ions can be detected drifting down wind from an operating direct current line. Although there is some concern about air ions from transmission lines, research has not shown any adverse effects to humans, plants or animals. *High voltages will cause the breakdown of air molecules resulting in charged particles called ions. This phenomenon is called* ***corona***. Corona can cause an audible sizzling noise near the transmission lines. Audible noise from corona generally increases in wet weather. It may also cause interference with communication signals especially AM radio reception.

Current flowing on any electrical line causes a *magnetic field* to build up in the air around the line. This is also true of the wires in a building. There are *some scientific studies that implicate prolonged exposure to magnetic fields as a cause of some types of cancer, but these studies are not conclusive*. Air is a poor conducting medium for a magnetic flux and therefore, the magnetic field that does exist about a transmission line decreases to a negligible level a short distance from the line. How the conductors are arranged on the structures can help to achieve cancellation of the magnetic field. In the case of underground transmission lines, earth does not provide shielding against magnetic fields but magnetic field cancellation may be achieved by the way the conductors are installed in the earth. Presently there are no scientific studies that directly link magnetic fields from electrical lines to human health problems.

Transmission lines also produce an *electric field* in the air near the lines. The electric field is stronger as the voltage increases. Electric fields have not been linked to human health problems. A static voltage may build up in metal objects that are very near a high voltage transmission line. Buildings with a metal skin located close to a high voltage transmission line may produce annoying discharges when a person touches the metal building. This problem can be cured by grounding the metal building to the earth.

Needless to say, some persons find high voltage transmission lines to be undesirable and will do whatever it takes to block their construction. But without transmission lines, electrical power cannot be transported from the generating plants to the customers. A trade-off is to locate generating facilities near large population areas.

Targeted Area Planning: Targeted area planning is a process where utilities build smaller sized generating facilities near the locations where power is needed. The objective is to reduce the need for high voltage transmission lines. When electrical power must be transported long distances such as several hundred miles, very high voltages are needed to prevent excessive losses. By locating generating facilities near points of use, shorter transmission lines operating at lower voltage can be used. The challenge is, therefore, to find acceptable locations for the generating facilities.

Electric Utilities: In the early 1900s electric power was only available to homes and businesses in highly populated areas. It was too expensive to extend electric distribution lines out into sparsely populated rural areas. In the early years there were privately owned electric utilities, investor owned electric utilities, and municipal electric utilities. These utilities seldom extended electrical distribution lines outside of towns and cities. In 1935 the U.S. Congress passed the Rural Electrification Act which authorized the establishment of member owned Rural Electric Cooperatives for the purpose of extending electrical power lines out into rural areas. The Rural Electric Administration of the U.S.D.A. made low interest loans available to finance electrical line development in rural areas. By the 1940s utility electric power was available in most areas of the U.S.

Electric utilities serving local areas take power from the transmission system or from generating facilities and distribute it to customers in that local area. These may be *investor-owned utilities, member owned rural electric cooperatives, municipal utilities, and in some cases privately owned electric utilities*. Customers such as homes, farms, commercial businesses, and small and moderate sized manufacturing companies receive their electrical power from the distribution system. Large factories and complexes such as some shopping malls use such a large amount of power they are served by a transmission line and sometimes operate and maintain their own substation.

Electrical Distribution: Transmission system high voltage is reduced by transformers at a substation, and run along streets and roads in the local area to supply customers. A *substation* may have from one to several distribution circuits serving customers. Power is generated and moved over the transmission system as 3-phase alternating current with a frequency of 60 cycles per second (Hz). Most distribution circuits from a substation start out as 3-phase circuits, but if there are no customers desiring 3-phase power, some of the distribution wires are discontinued to minimize cost and only single-phase power is available on those lines. Two wires are needed for single-phase power. Three-phase power can be made available in the future by adding more wires.

The transformer in the typical substation in the Eastern U.S. has three windings connected in a radial manner called a wye. This is shown in Figure 225.2. The common point where the windings are joined is connected to the earth usually by ground rods and bare copper wires in the earth beneath the substation. A typical 3-phase circuit leaves the substation consisting of four wires. One wire connects to the end of each transformer winding (three wires total) and the fourth wire (neutral) connects to the common point and ground rods beneath the substation.

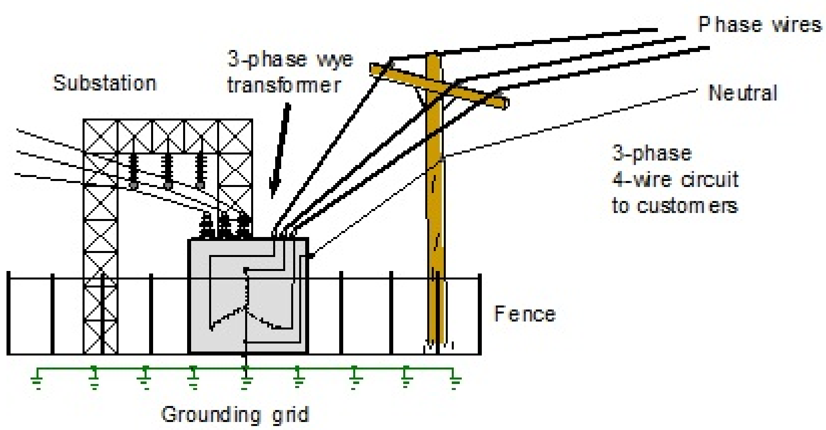

Figure 225.2 *Simplified diagram of a distribution substation with a wye connected transformer lowering the transmission voltage to a typical distribution voltage. The common point of the transformer is connected to the earth by means of ground rods and bare wires beneath the substation. One 4-wire circuit with a grounded neutral wire is shown leaving the substation.*

The circuit wires leaving the substation are frequently called primary wires. They connect to the primary side of the customer transformer. Most residential and many farm and small commercial customers only use single-phase power. It takes one transformer with one wire connected to the primary neutral and one wire connected to a primary phase wire to supply single-phase power to a customer. A grounded distribution line is shown in Figure 225.3. The primary phase wires are mounted to the top of the pole on insulators. When there is more than one phase wire, there is usually a cross-arm connected to the pole to support the wires and insulators. The neutral wire is usually connected below the phase wires and it is generally mounted to the side of the pole. The conductors entering the view of Figure 225.3 from the left are three phase wires and a neutral wire. One of the phase wires ends at that second pole and only two phase wires continue on to the next pole. The pole at the right in Figure 225.3 shows a single-phase transformer connected to one phase wire and the neutral wire to supply single-phase 120/240 volt, 3-wire power to a customer. Extending off the diagram to the right is a single-phase primary distribution line with one phase wire and a neutral wire. From this point only single-phase power can be supplied to customers. Also note in Figure 225.3 that the neutral wire is grounded at several of the utility poles. The *National Electrical Safety Code* which is used as a construction guideline for utilities requires the primary neutral wire to be grounded a minimum of four times per mile. In most cases these grounds are at customer transformers, but sometimes a ground is placed at a pole without a transformer. This is called a multi-grounded, 4-wire, wye primary distribution line. A major reason for grounding the distribution line neutral to the earth is to help with lightning protection and to maximize safe operation of the distribution line.

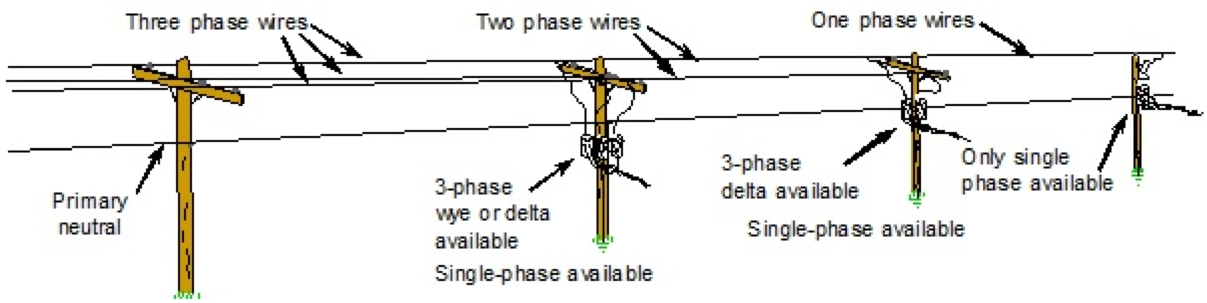

Figure 225.3 *A multi-grounded primary distribution line can have up to three phase wires and one grounded neutral wire. At some points there may be only one phase wire and the grounded neutral wire present.*

A 4-wire multi-grounded wye primary distribution line will have one voltage between phase wires and it will have another voltage between each phase wire and the neutral wire or earth. The phase-to-phase voltage will be 1.73 times the phase to neutral voltage. Typical multi-grounded primary distribution lines operate at 8300/4800 volts, 12,460/7200 volts, and 24,900/14,400 volts. The higher voltage listed is the phase-to-phase voltage and the lower voltage is the phase-to-neutral voltage. The transformer for a single-phase customer is connected on the primary side to the phase-to-neutral voltage.

Primary/Secondary Neutral Bond: Experience has shown that maximum safety to the customer can be achieved by connecting the customer neutral wire to the utility primary neutral wire. If for any reason accidental contact should occur between the customer secondary wires and the primary ungrounded wires, a direct connection between the neutral wires would allow fault current to flow and blow the fuse on the primary side of the transformer, thus de-energizing the primary wire. The standard connection at every customer transformer is to connect the customer neutral wire to the utility primary neutral wire. This connection is shown in the schematic diagram of the single-phase 120/240 volt customer transformer in Figure 225.4.

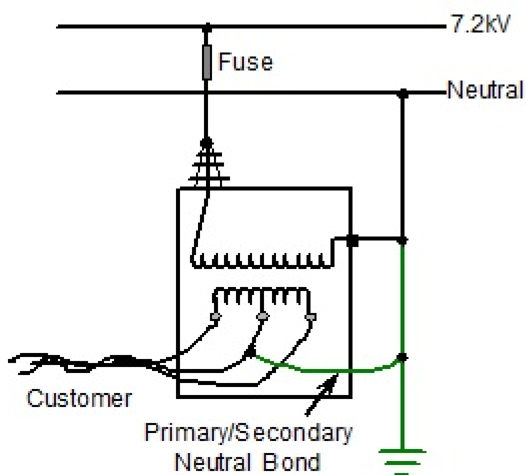

Figure 225.4 *In most cases the secondary neutral wire to the customer service is bonded with a wire to the utility primary neutral wire at the customer transformer.*

The connection between the primary and secondary neutral wires is called a *primary/secondary neutral bond*. In limited cases the utility may decide a customer is better served by removing this neutral bond wire at the transformer. A special procedure is followed, prescribed by the *National Electrical Safety Code*, to remove the bond wire and still maintain maximum safety to the customer. The primary/secondary neutral bond is sometimes removed in cases where there is a source of neutral-to-earth voltage arising from off a customers property that cannot be reduced to a level considered acceptable.

Neutral-to-Earth Voltage: As might be expected, connecting the neutral wire to the earth at many points makes the earth a parallel path to the neutral wire. Anytime current is flowing on the neutral wire of a multi-grounded distribution line, current will also flow in the earth. *It is common to have a small amount of current flowing in the neutral grounding wire at each pole*. A sensitive ammeter can be used to measure the current flowing on a pole grounding wire. A ground rod will have a resistance-to-earth, and for damp unfrozen sandy loam soils the resistance may be as low as 15 ohms. This current flowing to ground at a pole, according to the equation called Ohm's law, will result in a voltage between the pole ground wire and the surrounding earth. Assume the current flowing to earth at a pole ground is 0.03 amperes (30 mA). This will result in 0.45 volts between the pole ground wire and the surrounding earth if the ground rod resistance is 15 ohm. *This phenomenon is called neutral-to-earth voltage* and is generally present to some extent on any multi-grounded primary distribution line. Current will flow in the transformer primary winding when the customer is drawing power. The current in the primary neutral wire at the transformer will return to the substation by means of the neutral wire and some will return through the earth.

By measuring the neutral-to-earth voltage, as illustrated in Figure 225.5, at a pole ground or a service ground, resistance of the ground rod can be determined using Ohm's law. The current flowing in the wire to the ground rod must also be measured. For example, assume the neutral-to-earth voltage at the pole in Figure 225.5 is 1.2 volts, and the current flowing on the pole grounding wire is 40 mA (0.04 A). The resistance is determined by dividing the neutral-to-earth voltage by the grounding wire current, and in this case the resistance of the ground rod is 30 ohm (1.2 V / 0.04 A = 30 ohm). Such measurements along a utility distribution line must only be made by trained utility personnel. *The public should never make measurement at utility equipment including a ground wire at a utility pole.*

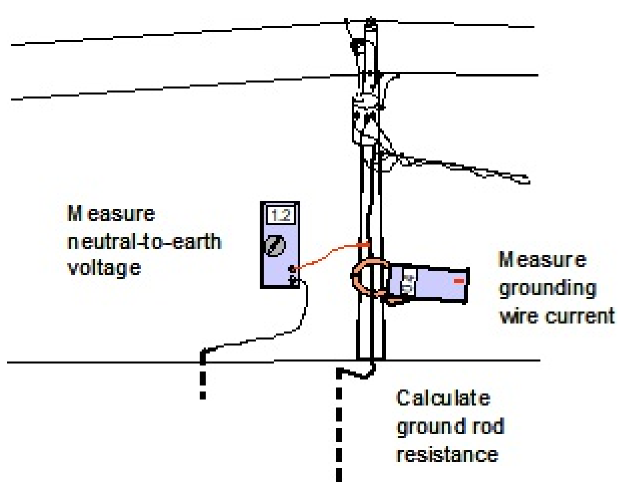

Figure 225.5 *Neutral-to-earth voltage is created when current flows between the earth and the neutral wire of a multi-grounded primary distribution line.*

Conclusions: Most of the electrical power is produced by large generating plants in locations often long distances from the customers to be served. A network of transmission lines is needed to transport this power to communities where it can be distributed to individual customers. Resistance of the wire is a limiting factor when moving electrical power through wires. A relationship known as Ohm's law quantifies the power loss when a high level of current flows against this wire resistance. Electrical power can be transported at a lower current if the voltage in increased resulting in a greatly reduced power loss. High voltage is essential to transporting electrical power long distances.

A reliable source of electrical power to customers can be maintained when different utilities cooperate and share their facilities. Individual utility transmission lines in large regions of the country are interconnected at strategic points to form what is known as an electric power grid. Utilities are constantly buying and selling electrical power to each other.

Substations are facilities where the voltage of the electrical system is changed. At the generating plant a substation transformer will raise the voltage for transmission to distant locations. In a local community a substation transformer lowers the voltage to the level desirable for distribution to customers. In the Eastern U.S. distribution of power to customers is generally by means of power lines with one wire connected to earth. This results in a small current flow in the earth, but it improves the reliability and safety of the power system.