STUDENT GUIDE

Energy Industry Fundamentals

CEWD
CENTER FOR ENERGY WORKFORCE DEVELOPMENT

MODULE

4

ELECTRIC POWER TRANSMISSION

STUDENT GUIDE

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MODULE 4

ELECTRIC POWER TRANSMISSION

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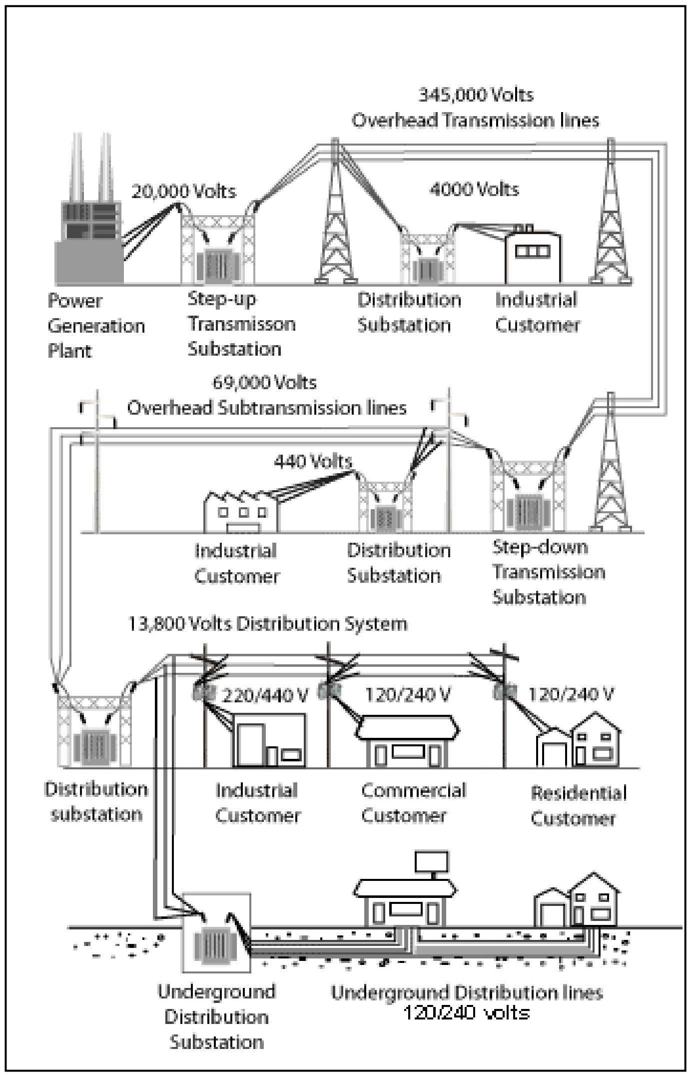
Unit A: Introduction to Electric Power Transmission

UNIT A: INTRODUCTION TO ELECTRIC POWER TRANSMISSION

Module 3 covered many different ways of generating electrical **power**. Regardless of what type of method is used to generate power—nuclear, gas, wind, or other—all power generation plants use a **transmission system** to send the electrical power they produce to end users. Generation sources require specially designed transmission systems to **step-up** the output **voltage (volts)** from the production system to higher voltages for interconnection with power pools/grids.

The transmission system delivers power directly to **substations** of a specific utility company and to larger industrial consumers at voltages of 69 kV and above. The transmission system is generally connected to a **subtransmission system**, which delivers electrical power to large commercial customers at voltages between 35 kV and 69 kV. The subtransmission system is also connected to a **distribution system**. Distribution systems deliver electrical power to residential customers and to smaller commercial customers at voltages of 35 kV and below.



Transmission System Overview

Electric power transmission, also referred to as high voltage electric transmission, can be defined as the bulk transfer of **electrical energy** from power generation plants to substations. The transfer of electrical energy from substations to the customer is referred to as distribution, which is the focus of Module 5.

Transmission serves two main purposes, to transfer electricity from generation plants and to interconnect various systems. This interconnection of transmission lines is often referred to as **electrical power grids** or, simply, "the grid." Most of the power generated in the station passes through the **generating plant switchyard** to the transmission system.

About 5–8% of the generated power is used within the plant to operate the equipment necessary to run the plant. The switchyard contains all the equipment necessary to transform and route power: buses, **circuit breakers**, disconnects, **transformers**, protective relays, monitoring and controlling devices, **insulators**, and supporting structures, which together move the power from the **generator** to the transformer and then to the transmission system. (A bus is a specially designed **conductor** having low **resistance**.) Other switchyards house similar protective relays, monitoring and controlling devices, insulators, and supporting structures, which move the power from the transmission system to the distribution system.

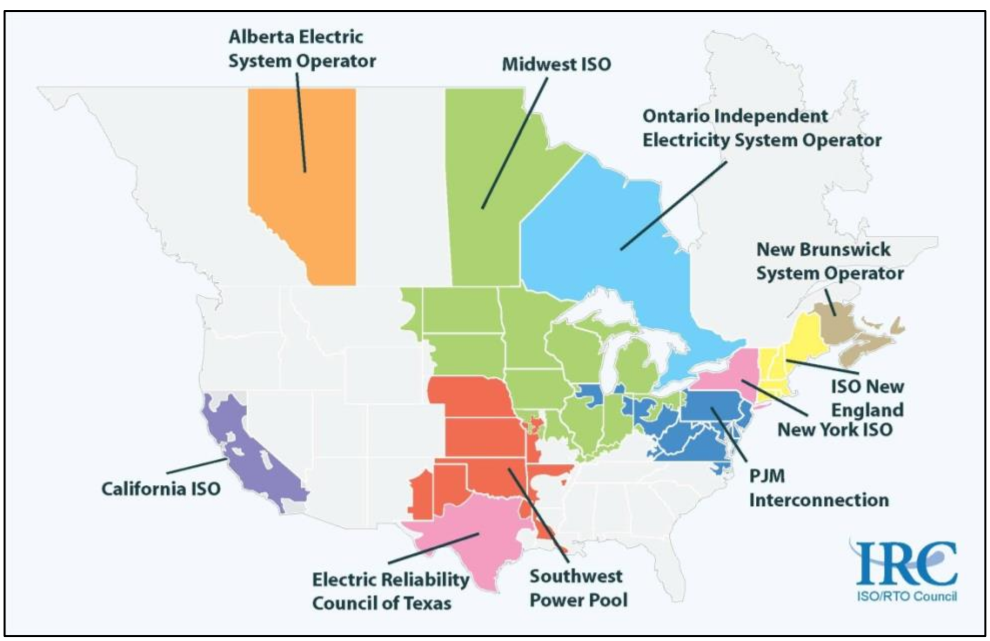
Did you know?

Early Transmission

In the 19th century when electricity was first being used for larger purposes, the generation source had to be right next to the equipment or system that was using the electricity that was generated. Even when electricity was first being transmitted through early transmission lines, it was so inefficient that the lines were not longer than one mile from the power generation source.

Various Power Pools/Grids

A power pool or power grid consists of interconnected networks for delivering electricity from suppliers to consumers. The transmission system serves to connect different power pools or grids. Examples of the different entities that make up power grids were covered in Module 1. Power grids and their operating authorities are responsible for the safe and reliable operation of the electric transmission system from producer to customer.



Major power pool or power grid interconnections are often connected by **direct current (DC)** lines. Using direct current connections addresses the need to synchronize **alternating currents (AC)** from interconnected systems. This will be discussed in more detail later in this module.

Very High Capacity Customers

Some customers are connected directly to the transmission system at high voltages. Examples of some of these types of customers include manufacturing and industrial operations, nuclear plants, technology and research operations, educational institutions, and hospitals.

Substations and Subtransmission Systems

The high voltages that are required for bulk electricity transmission are too high for the voltages that are needed for most consumer applications. Lower voltage levels are required for electricity to flow safely through smaller cables and distribution lines, save money, and protect customers.

At transmission interconnection intervals such as substations, some of the electrical energy is tapped off of the transmission lines. These substations step the voltage down to lower voltage levels with large power transformers.

Substations are interconnected and dispersed within high-voltage transmission lines and subtransmission lines to provide additional system control facilities to detect abnormalities that could cause system interruptions by monitoring the lines' **currents (amps)**, voltages, and power flows. Transformer circuit breakers protect equipment from being overloaded. The lower-voltage output circuits from the substations are called **distribution circuits**.

500 kV to 230 kV single-phase transformer

500 kV gas breaker

Substations vary in size depending on the system they are servicing. Most substations are constructed in an area where the vegetation has been removed and the lot is filled with gravel. They are typically fenced and gated for safety and security.

Substations are interconnected to the transmission system and distribution system by two methods:

- High-voltage transmission circuits directly **step-down** electrical energy to distribution connections, such as 138 kV or 230 kV transmission circuits supplying substations that normally provide 13 kV distribution circuits.
- High-voltage transmission circuit-supplying **switching stations** step-down voltages to a subtransmission level voltage, commonly in the range of 26 to 34 kV. The subtransmission circuits' voltage level can easily be routed along public streets on wood poles or through underground cables to industrial, commercial, and utility substations. These subtransmission-supplied substations provide system monitoring and control for distribution circuits in the 4 to 13 kV range.

Substations can also perform **transmission switching**, which is the connecting and disconnecting of transmission lines or other components to and from the system.

☼ Career Profile: Electrical Engineer

Sarah H. is an electrical engineer. Most electrical engineers design, develop, test, and supervise the manufacture of electrical equipment. Some of this equipment includes electric motors; machinery controls; radar and navigation systems; and power generation, control, and transmission devices used by electric utilities.

Sarah's job is that of a more traditional electrical engineer in that she works for a power company, and her job focuses on the supply and transmission of electrical power. Sarah specializes in power-systems engineering, and she is classified as a substation engineer.

Sarah is tasked with a lot of engineering design projects. She researches and prepares high-voltage substation schematics and calculations, so she utilizes her knowledge about design, specifications, layouts, and management of high-voltage substations.

© 2011 OSHA

As far as her education, Sarah says, "A bachelor's degree in engineering is required for almost all entry-level engineering jobs. In addition to a bachelor's degree, engineers that want to offer their services directly to the public must be licensed as well."

Sarah says, "In addition to performing my on-the-job duties, it is important for me to find time to keep up with continuing education credits so I can try to stay up-to-date with rapidly changing technologies." Engineers trained in one specialty may work in related specialties. This flexibility allows employers to meet staffing needs in new technologies and specialties.

Electric Power Transmission Process

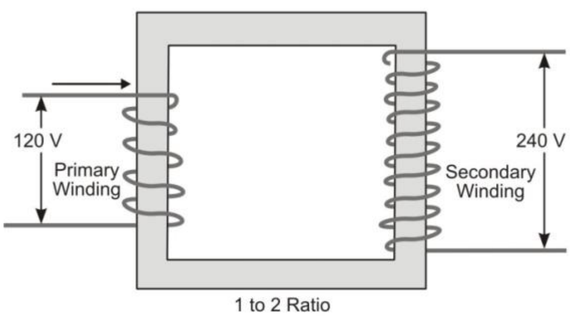
The movement of electricity through the transmission system is a complex process. Electricity produced by power generation plants is first routed to substations at or near the plant. These substations use transformers to “step-up” the voltage of electricity in preparation for movement through the transmission lines. Required voltage levels depend on the distance that electricity must travel through the transmission system. Electricity then exits the transmission system at distribution substations where it is “stepped-down” to lower voltages for distribution to consumers.

> Focus on ...
>
> **Voltage Differences**
>
> A generating plant’s typical output voltages are between 12 kV and 30 kV.
>
> Typical transmission voltages range from 138 kV to 765 kV.

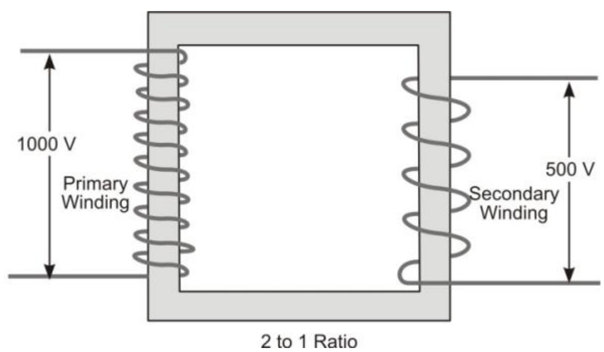
Transformers

Power that is generated at power plants must be collected and delivered to the transmission system at the voltages that match transmission requirements. In modern power plants, the electrical power leaving the generator travels to a main power transformer, which steps up the generated voltage to local grid levels.

A transformer is an electrical device by which alternating current of one voltage is changed (transformed) to another voltage. They operate on the theory of mutual inductance. A basic transformer consists of two sets of windings, or turns, coiled around an iron core and placed in a covered tank. The primary winding is connected to the source (input) voltage. The secondary winding is connected to the **load** (output). There is no physical connection between the windings.



Step-up transformer



Step-down transformer

As alternating current flows in the primary winding of the transformer, a magnetic field or flux is developed in the iron core. As the current reverses direction, the magnetic field also changes direction. This action induces an alternate voltage in the secondary winding, and if the secondary circuit is closed, an alternating current will flow. When there is the same number of turns in the primary and secondary windings, the voltage will be the same in both the source and the load circuits.

Focus on ...

Transformers

Transformers operate on two basic principles:

1) Whenever an electric current flows, there is magnetism around it.

2) Whenever a magnetic field changes (by moving or by changing strength), voltage is created. If there is a wire close by when this happens, then a current will flow in the wire as the magnetism changes.

Step-Down Transformer © 2011, OSHA

If there are more turns in the secondary winding than in the primary winding, the transformer is said to be a **step-up transformer** and the voltage in the secondary circuit will be greater than the voltage in the primary circuit. A **step-down transformer** has less turns in the secondary winding than in the primary winding, and voltages are higher in the primary circuit than in the secondary circuit.

A transformer can only transfer power, not produce it. Besides the main power transformer that steps voltage up to transmission levels, a variety of other transformers are found along the transmission and distribution lines that adjust voltages for the power grid and that step-down voltages to levels needed by various consumers.

If there could be an "ideal" transformer with no power losses, the power in the primary would equal the power in the secondary exactly. In any AC circuit, the power equals the voltage times the current ($P = I \times E$). An ideal step-up transformer with a one-to-two ratio would double the voltage, but the current will be reduced by half. For example, if 200 amperes of current were flowing at 1,000 volts in the primary winding, 100 amperes of current would be flowing at 2,000 volts in the secondary winding. In a step-down transformer, the voltage is decreased; therefore, the current will increase at the same ratio.

Science Connections

Voltage and Current

Voltage is a measure of energy carried by a charge. Voltage is supplied by a power source. Current is the rate of flow of charge.

Voltage attempts to make a current flow. Voltage is sometimes described as the "push" or potential energy of the electricity. Current is the flow of energy.

It is possible to have voltage without current, but current cannot flow without voltage.

Transmission Switching Stations

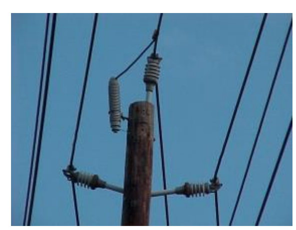
© 2011 Berkeley Lab

Transmission system switching stations provide control facilities for monitoring the system operation and provide connections to other transmission systems. Switching stations function as a transmission system control facility by monitoring the lines' currents, voltages, and power flows to detect abnormalities that could cause systems interruptions.

These stations are also used to interconnect transmission circuits that operate at different voltage levels. Switching stations increase the overall delivery system reliability through their interconnection of power production sources and regional power pools. These interconnections increase system reliability by increasing the potential sources of energy for the delivery system and alternate paths for routing electrical energy in the event of an operational emergency or to perform line construction/maintenance.

Transmission line outages for construction/maintenance can be especially difficult, or sometimes impossible, during peak customer load periods. This has caused many utilities to develop work practices and improve the technical skills of associates to maintain transmission lines/circuits while they remain in service carrying energy to customers.

Typical subtransmission-level customers are moderately large users of electrical energy commonly requiring multiple circuits to supply their needs. The multiple circuits may be required because of the customers' load requirements or necessary for increased reliability. Examples of subtransmission customers are colleges, hospitals, and industrial processes.



A subtransmission line

Systems and Equipment

There are numerous systems and essential equipment that comprise the transmission system. Perhaps the most obvious systems are the ones we can see. Most of us are familiar with the sight of transmission lines in our cities. These transmission lines are the foundation of the United States electric transmission system.

Transmission Lines

There are many different designs of transmission lines that can usually be categorized within two main types: overhead transmission lines and underground transmission lines.

Overhead Transmission Lines

The majority of transmission lines in the United States are overhead transmission lines. Overhead transmission lines consist of heavy cable strung between **transmission towers**. Overhead alternating current (AC) transmission lines typically carry three-phase current. The voltage carried by the line varies depending on the particular system or grid. There are different types of transmission towers to accommodate varying transmission needs. Three-phase AC transmission towers accommodate three lines (or multiples of three), while direct current (DC) transmission towers typically only carry lines in pairs (one positive current and one negative current).

Focus on ...

Transmission Line Routes

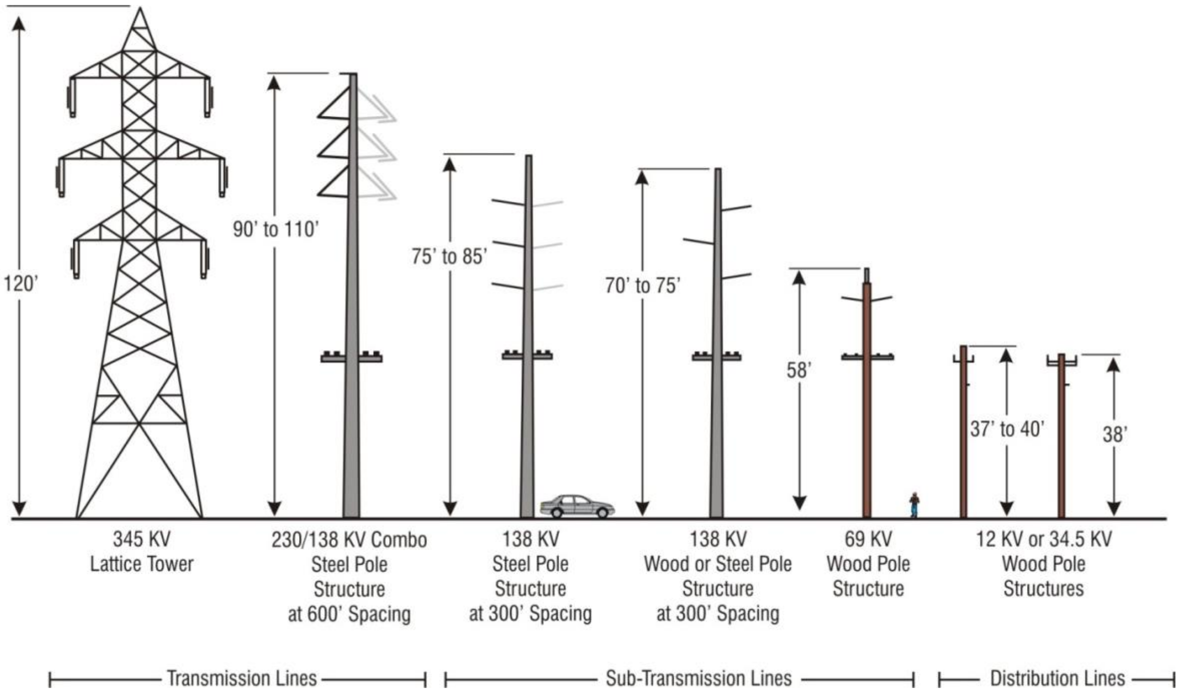
Transmission line routes are selected with consideration of the following factors:

- Avoidance of sensitive areas (habitats, wetlands, parks, recreational areas)
- Avoidance of farmland
- Avoidance of historic buildings
- Avoidance of residential areas

(Argonne Laboratory, 2007)

Design Specifications

The design of the equipment used in transmission line systems is usually based on the voltage load that the system will be carrying. The voltage affects the transmission tower design and dimensions, span length, conductor materials, and mechanical strength. As transmission line voltage increases, typically there is also an increase in the following: the height of the transmission tower, insulator size, distance between conductors (lines) on the tower, and the size of right of ways. These changes in engineering and design are created with the intent of providing isolation of the electric current, since an increase in voltage results in an increased tendency of arcing.



Towers

High-voltage, overhead transmission towers are typically tall metal structures generally composed of steel or aluminum alloys. Tower designs typically include lattice or pole designs. The basic function of a transmission tower is to isolate the transmission lines by elevating them. See Figure 4A.1.

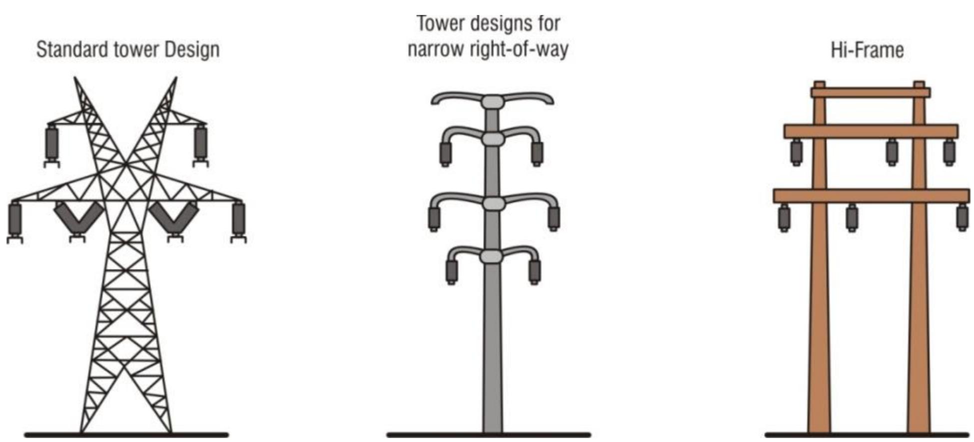


Figure 4A.1 Towers

The elevation and clearance of high-voltage transmission lines is a safety precaution. Some lower-voltage lines are carried by wooden towers that are not as tall. Transmission towers are designed to keep the transmission lines from contacting any objects in the surrounding environment, and to keep the lines from touching each other.

Conductors

Overhead transmission lines consist of the "power line" which is also called the cable or conductor. Electricity travels through the path of least resistance, so lines are made from materials that electricity can travel through easily.

Overhead lines are usually composed of several strands of an aluminum alloy coupled with steel strands that serve as reinforcement material for added strength. The majority of overhead transmission lines are not insulated because they are erected high up on tall transmission line towers. Insulators such as glass or fiberglass do not allow electrical current to flow through the towers.

The characteristic of materials to allow flow or not is known as its resistance. Conductors have low resistances and insulators have very high resistances.

Why is wire resistance important? Wire resistance opposes current flow. Forcing current through the resistance in a conductor makes heat. The heat is wasted power. Wasted power results in increased cost to the consumer. So what can be done? Raising voltage with a transformer lowers current proportionally. Lower current reduces power loss in the form of heat. Lowering current by raising voltage makes it possible to use smaller conductors to efficiently deliver large amounts of electrical energy over long distances. That is why energy suppliers use transformers to raise voltage to high levels for power transmission and distribution. At the point of use, voltage is stepped-down with transformers to meet the customers' needs.

Let's look at an example. A million watts of power can be delivered in various ways.

Quick Facts

Conductors

All conductors have wire resistance based on:

- The material the conductor is made of. Different materials of equal size and length can have varying amounts of resistance. Copper has less resistance than aluminum.
- The conductor's diameter. The larger the diameter, the less the resistance. They are also heavier and cost more.
- The conductor's length. Increasing the length of a conductor increases its resistance.
- Temperature. Increasing the temperature of a conductor increases its resistance.

(Source: PSE&G)

Remembering our formula for power (P = I × E), two possibilities are:

- 1,000,000 watts = 1,000 amps × 1,000 volts, or
- 1,000,000 watts = 10 amps × 100,000 volts

At 1,000 amps, the power loss could be very high. If the conductor carrying the load had a resistance of only 1 ohm, the power loss ($P = I^2R$) would be the entire million watts:

- 1,000 amps × 1,000 amps × 1 ohm = 1,000,000 watts lost

Science Connections

Commonly Used Formulas

Ohm's Law:
Voltage = Current × Resistance,
E = I × R or E = IR

Power in Watts = Current × Voltage,
P = I × E, or P = IE

Since E = I × R you can substitute I × R for E in the Power equation to get $P = I \times I \times R$ or $P = I^2 \times R$ or $P = I^2R$

But if we use a transformer to step-up the voltage to 100,000 volts, the current drops to 10 amps and the power loss will be:

- 10 amps × 10 amps × 1 ohm = 100 watts lost

Obviously, high voltage and low current is the most efficient way to transmit power.

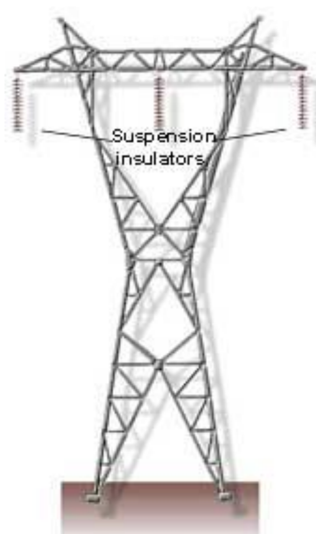
☼ ACTIVITY: Wire Gauge and Resistance

Using the library, Internet, or other resources, research the impact of wire gauge on resistance in electrical circuits.

Research how different transmission conductors are created (design, materials), and how those variables affect electric current transmission.

Insulators

Insulators support the conductor and are used at conductor connection points. Insulators are designed to prevent line contact that would result in a fault and to limit conductor sway. Insulators may support the conductor above the tower attachment or be a suspension-type design in which the conductor hangs below the tower attachment (see images below). Insulators are usually made out of specialized ceramics such as porcelain, glass, or glass-reinforced polymers. Insulator design is based on line voltage.



Did you know?

Early Insulators

The first type of electrical transmission system that used insulators was the telegraph system. Early engineers found that the direct attachment of telegraph lines to their wooden support structures caused very poor transmission of telegraph signals.


©2011 NIH

Lightning Protection

To control the effects of a possible lightning strike on energized lines and equipment, transmission towers are equipped with specialized equipment to prevent or reduce any damage that could be caused by the strike. One example is the extra set of wires that run along the upper extremes of the transmission tower above the actual conductor lines. These wires, called **ground wires** or shield wires, are attached directly to the transmission towers (no insulators) so that in the event of a lightning strike, the current would travel through the shield lines and down the transmission tower to the ground. Another method of lightning protection is through the use of lightning arresters (also called surge arresters). Lightning arresters work by limiting surge voltages due to lightning strikes to prevent damage to equipment.

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Right of Way

Transmission towers and lines are protected by a **right of way** (ROW). The right of way for a transmission system consists of the land set aside solely for the use of transmission towers, lines, and other facilities. Right of ways serve as safety mechanisms to maintain clearance areas between the transmission lines and surrounding structures or trees and other vegetation.

Focus on …

ROW

Factors affecting ROW design:

- Land slope
- Soil type
- Clearing requirement
- Visual impact
- Sensitive habitats
- Significant existing structures

(Argonne Laboratory, 2007)

Right of ways not only provide a safety margin between transmission lines and surrounding structures, but they also provide easy access routes for service workers to inspect and maintain the lines and other system components.

☼ ACTIVITY: Electric Power Transmission and "NIMBY"

When it comes to improving the transmission system to meet our nation's growing electricity demands, companies not only face financial complications but also social complications. The concept of "NIMBY" (Not in My Backyard) has proven to be a strong influencing factor on the advancement of much-needed energy infrastructure updates.

Many environmental interest groups or local community committees fight the development of power generation and transmission projects that are in close proximity to their locations, even though these improvements are typically beneficial to all members of the general public.

The U.S. Chamber of Commerce has reported that many potential transmission projects have been delayed or cancelled due to regulations and lawsuits imposed by NIMBY-minded adversaries.

- How can NIMBY affect the economy, jobs, and growth?
- How can NIMBY affect the advancement of the Smart Grid?
- Has NIMBY affected any energy-related projects in your area?

Underground Transmission Lines

In highly populated areas, some transmission lines are placed underground. The lines may be buried or placed in tunnels or trenches. While overhead transmission lines are essentially cooled by air, underground transmission lines must be cooled by other means. Generally, underground lines are cooled by specialized oil cooling systems.

While overhead transmission lines are essentially insulated by the air, underground transmission lines are usually insulated by some type of covering or sheath.

Underground transmission lines may reduce impacts such as visual impacts, reduced land use, and reduced ROW maintenance; however, the construction of underground transmission lines is typically more expensive and requires more complicated engineering than overhead transmission lines.

Electric Power Transmission Principles

As we have already mentioned throughout this course, there are two main types of currents used in electricity applications: direct current (DC) and alternating current (AC). In DC, an electric charge flows in one direction. In AC, an electric charge flows back and forth, rapidly reversing direction many times each second. Whether AC or DC current is used in an electrical application often depends on the type of voltage source.

An AC voltage source reverses the positive and negative terminals many times per second. In the majority of AC circuits, the voltages and currents cycle at a rate of 60 times per second. This cycling is called the **frequency**. Frequency is measured in cycles per second or **hertz (Hz)**. Commercial power generation companies in the United States utilize a 60-Hz current.

As mentioned earlier, AC transmission lines typically carry a three-phase current, and the voltage varies depending on the particular system or grid. DC transmission towers typically only carry lines in pairs, one positive current and one negative current.

☼ ACTIVITY: Using an Oscilloscope to Examine AC Waveforms

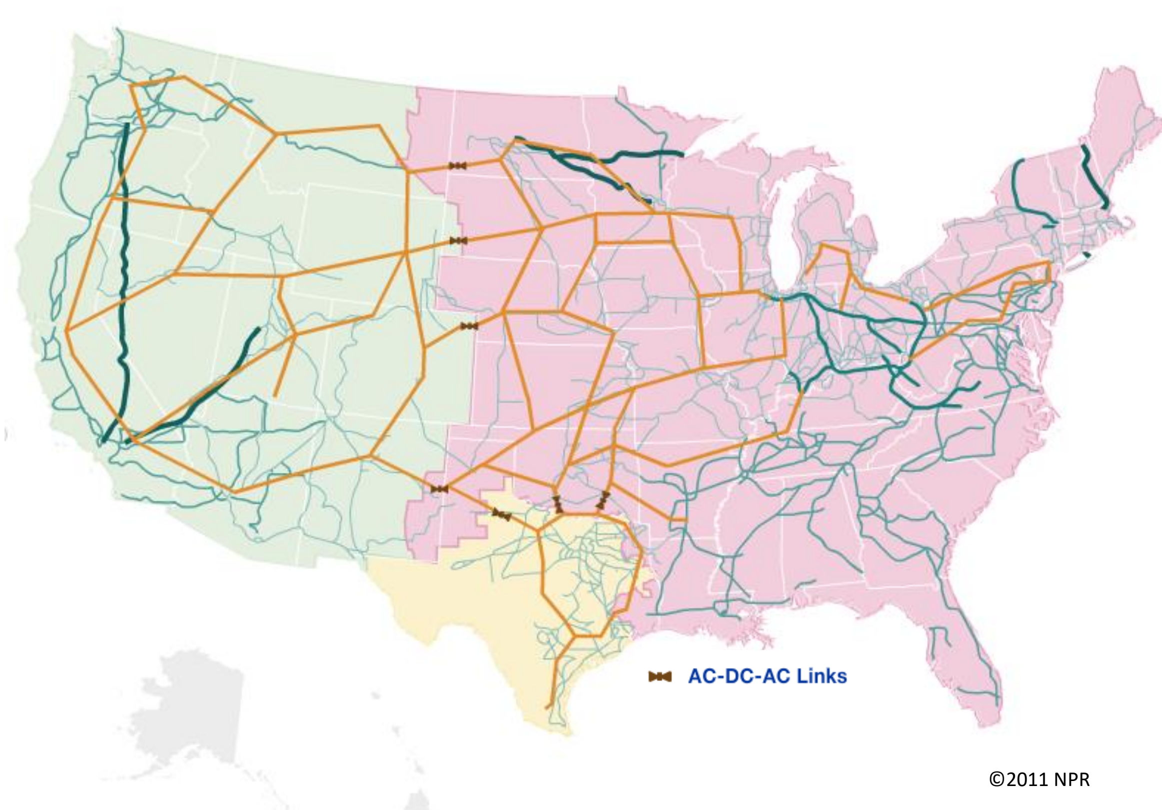
Work as a group to use an **oscilloscope** to examine an AC waveform and determine the phase difference between two signals of equal frequency.

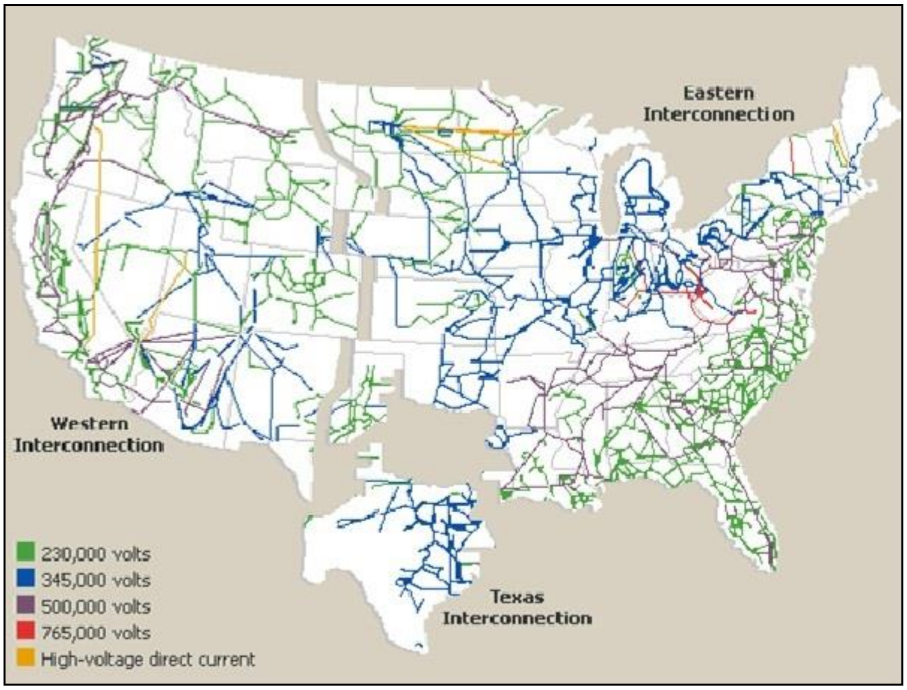
High Voltage Electric Transmission

Most transmission lines use three-phase alternating current (AC). High-voltage direct current (HVDC) is also used for transmission of large amounts of power over great distances (greater than 400 miles), or for the connection between various grids.

For the purpose of long-distance transmission, HVDC systems can be less expensive and typically have lower electrical losses than AC systems. However, DC systems must provide conversion and synchronization to AC systems to enter most transmission and distribution lines in the United States.

> **Did you know?**
>
> **High-voltage AC Systems**
>
> The significant development in the 1890s of power transmission with high-voltage lines using alternating current (AC) allowed the transmission of electrical power over longer distances, which was the beginning of the high-voltage AC system in use today.





Electricity must be transmitted at high voltages to reduce transmission losses. The transmission system operates at high voltages in ranges from 138,000 to more than 1,000,000 volts. As mentioned earlier, these high voltages are established at generation sources where the voltages are stepped-up by transformers so that more electrical energy can be transferred from one point to another with a minimum of loss.

Focus on ...

Transmission System Typical Voltages

Typical overhead transmission voltages used in overhead towers:
Overhead steel/aluminum towers/poles

- 138,000 volts or 138 kV
- 230,000 volts or 230 kV
- 345,000 volts or 345 kV (Interconnection with larger regional power pool/grid)
- 500,000 volts or 500 kV (Interconnection with major power pool/grid)

Typical underground transmission voltages used in underground cables:
Underground through pipe-type cooled cable

- 138,000 volts or 138 kV
- 230,000 volts or 230 kV
- 345,000 volts or 345 kV (Interconnection with larger regional power pool/grid)

☼ ACTIVITY: Creating a Voltaic Cell and Measuring Voltage

Work in groups to create a voltaic cell from a lemon or potato.

Use a voltmeter to demonstrate presence of voltage.

(There are many resources on the Internet for creating your own voltaic cell from fruits or vegetables.)

If possible, create multiple voltaic cells from different sources of fruits and vegetables. Do you notice any difference in voltages? What factors might account for the differences in voltages?

Transmission Limitations

There are limitations on the load that can be supported by transmission lines. Limitations include thermal and voltage constraints and other miscellaneous energy losses.

Thermal

The electricity that flows through high voltage power lines is opposed by electrical resistance. This resistance in turn produces thermal energy or heat. Lines have **thermal limits**; if the heat exceeds engineered limits, conductors can melt or even catch on fire.

©2011 Township of West Caldwell, NJ

The heating of transmission lines also causes the lines to sag. As the wires get warmer, they soften, causing them to lose some of their rigidness and sag under their own weight. Excessive line sag can cause a line fault caused by the arcing between the line and a surrounding object (tree, ground, other structure).

Voltage

As a result of transmission line **impedance** (the combination of **reactance** and resistance), voltages at the receiving end of a transmission line will be less than what was applied at the sending end of the line. This is called **voltage drop**. Voltage drop increases as transmission line length increases. Special voltage restraints are utilized to help remedy this issue and to prevent damage to utility and customer equipment.

Transmission line losses of voltage drops and power are usually caused by line impedances, which are unique to AC energy delivery systems like the 60-Hz one in use in the United States.

Energy Losses

While transmission lines operate with high voltages and are designed to be as efficient as possible, there are still energy losses that occur.

Equipment Losses

Many system losses are associated with losses in the equipment that electricity flows through. This equipment that serves electrical systems has resistance, so every line or transformer loses some power as it transmits energy.

Line Losses

When electricity is transmitted over long distances, some of the electrical energy dissipates in the form of heat. Additionally, as the distance traveled increases, the voltage decreases.

Corona Discharge

High voltages of 345 kV and above often experience small electrical discharges that are called corona losses. **Corona losses** are defined as losses that are a result of electrical stresses at the conductor surface and result in ionization of the surrounding atmosphere (air). These losses can also interfere with local radio transmission frequencies.

Did you know?

Power Line Hum

Corona discharge is one of the causes of audible noise (humming) from power lines.

Unit A Glossary

alternating current (AC)—an electric current that reverses its direction at regularly recurring intervals

circuit breakers—devices that protect a transformer from being overloaded with current and malfunctioning or destroying itself

conductor—materials such as copper and aluminum that allow electrical current to flow freely through them; in electric power transmission, conductor is also the term used for the actual "power line" or cable

corona losses—energy losses that result from electrical stresses at the conductor surface and result in ionization of the surrounding air

current (amps)—a flow of electrons in an electrical conductor; the strength or rate of movement of the electricity is measured in amperes (amps)

direct current (DC)—current which moves in only one direction; DC results from a constant polarity power source

distribution circuits—circuits that transmit lower voltages from the substation

distribution system—the portion of the transmission and facilities of an electric system that is dedicated to delivering electric energy to an end user

electric power transmission—the bulk transfer of high-voltage electrical energy from its source at generating plants to substations

electrical energy—electrical energy is the generation or use of electric power over a specified amount of time; electrical energy is expressed in kilowatt-hours (kWh)

electrical power grids—interconnected electric generation, transmission, and distribution systems over broad geographic areas

frequency—the number of cycles of alternating polarity per second; an AC voltage source reverses the direction of electric charge many times per second; measured in cycles per second (hertz or Hz)

generating plant switchyard—where power is transformed and routed to the transmission system

generator—the portion of the generating unit where the rotating mechanical energy is converted to electrical energy; it consists of a stator containing the armature (current) windings and a rotor (center shaft) that is turned by the turbine to rotate the magnetic field

ground wires—set of wires attached directly to the transmission tower so that current from a lightning strike flows to the ground; also called shield wires

hertz (Hz)—cycles per second; the unit of measurement for frequency

impedance—the total opposition to current flow caused by the combination of reactance and resistance; impedance is measured in ohms

insulators—materials such as glass and fiberglass that do not allow electrical current to flow through them; in electric power transmission, the term insulator also refers to the piece of equipment that is used to attach transmission lines that support the conductor and other conductor attachment points

load—the amount of electric power required by consumers (demand)

oscilloscope—an electronic measuring instrument that displays the waveforms created by an electrical current

power—in the context of electricity transmission, power is defined as a rate at which electricity (electrical energy) is produced; power is measured in watts (W) or megawatts (MW); power is a variable that must be considered when dealing with transmission system capability and capacity design and function

reactance—opposition to the flow of an alternating electric current caused by the buildup of electric or magnetic fields due to the current; reactance is measured in ohms

resistance—a measure of the degree to which an electrical component opposes the passage of current; resistance is measured in ohms

right of way (ROW)—the land set aside solely for the use of transmission towers, lines, and other facilities; right of ways serve as safety mechanisms to maintain clearance areas between the transmission lines and surrounding structures or trees and other vegetation

step-down—conversion of high-voltage electricity to lower voltage through the use of transformers at power substations

step-down transformer—a transformer that has more turns in the primary winding than in the secondary winding; voltages are higher in the primary circuit than in the secondary circuit

step-up—conversion of high-voltage electricity to higher voltage through the use of transformers at power substations

step-up transformer—a transformer that has fewer turns in the primary winding than in the secondary winding; the voltage in the primary circuit will be less than in the secondary circuit

substations—locations along a transmission or distribution route containing equipment to transform and route power

subtransmission system—a subsystem of the electric power transmission system that carries voltages that are reduced from the major transmission line system that is typically routed to distribution stations

switching stations—also known as switchyards, they are the area at a generating station that transforms and routes power to be entered into the transmission system

thermal limits—the maximum amount of power a transmission line can carry without experiencing heat-related deterioration

transformers—devices that transfer power from one circuit to another; step-up transformers increase voltage from the primary to the secondary circuit while lowering current proportionally, while step-down transformers lower voltage from the primary to the secondary circuit while raising current proportionally

transmission system—an interconnected group of electric transmission lines and associated equipment for moving or transferring electric energy in bulk between points of supply and points at which it is transformed for delivery over the distribution system lines to consumers or is delivered to other electric systems

transmission switching—the connecting and disconnecting of transmission lines or other components to and from the system

transmission towers—the rigid support structures that are used to support electric power transmission conductors (cables)

voltage (volts)—the difference in electrical potential between any two conductors or between a conductor and ground; it is a measure of the electric energy per electron that electrons can acquire and/or give up as they move between the two conductors

voltage drop—a reduction in voltage between the source and load in an electrical circuit caused by electrical resistance

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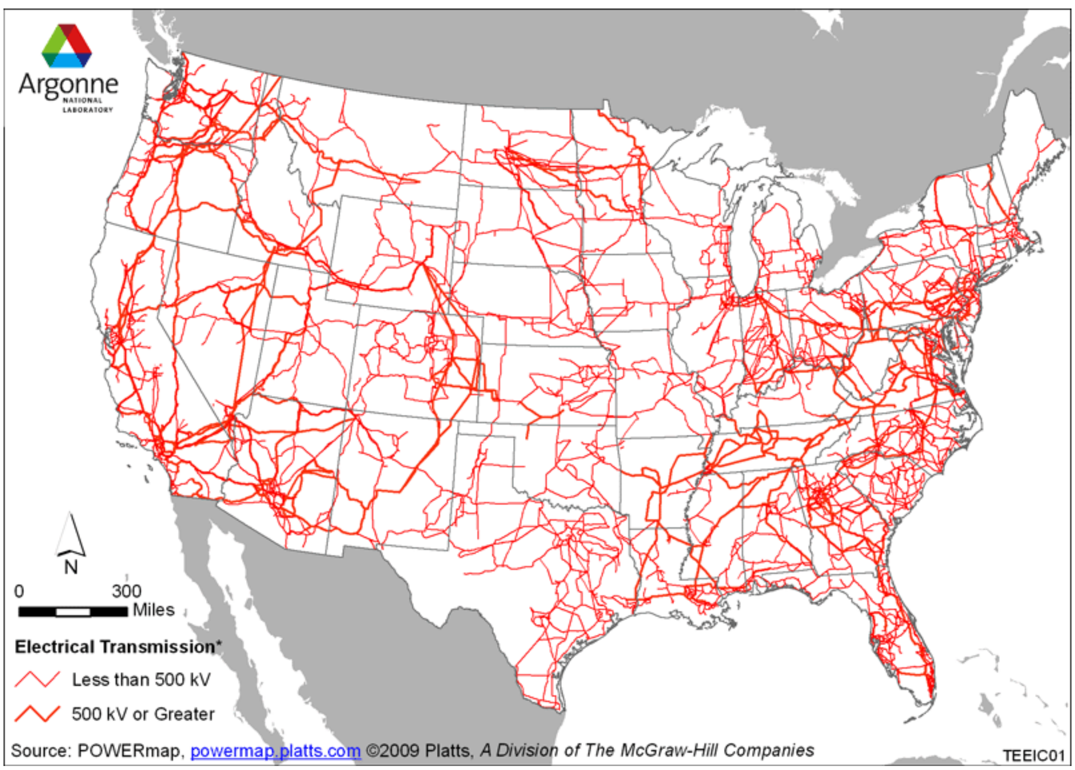
Unit B: Transmission Governance, Stability, and Emerging Technologies

UNIT B: TRANSMISSION GOVERNANCE, STABILITY, AND EMERGING TECHNOLOGIES

The National Electricity System

Transmission systems are designed to be efficient, safe, and reliable. Since electric transmission networks are essentially all interconnected into regional and national networks, there is some redundancy that provides for additional reliability of the system.

As mentioned in Module 1, the U.S. electric power system is an integrated system of interconnecting networks composed of generating plants, transmission facilities and lines, and local distribution facilities and lines. Generation, transmission, and distribution entities must work in a cooperative manner to provide reliable, adequate, and safe power to customers.



There are more than 200,000 miles of high-voltage transmission lines in the U.S. that move electric power from generating plants to local distribution systems to be sent to customers. These high-voltage transmission lines are also referred to as the transmission "grid."

The U.S. electric power system is an interconnection of three major systems, or grids: the Eastern Interconnection, the Western Interconnection, and the Texas (ERCOT) Interconnection. See Figure 4B.1.

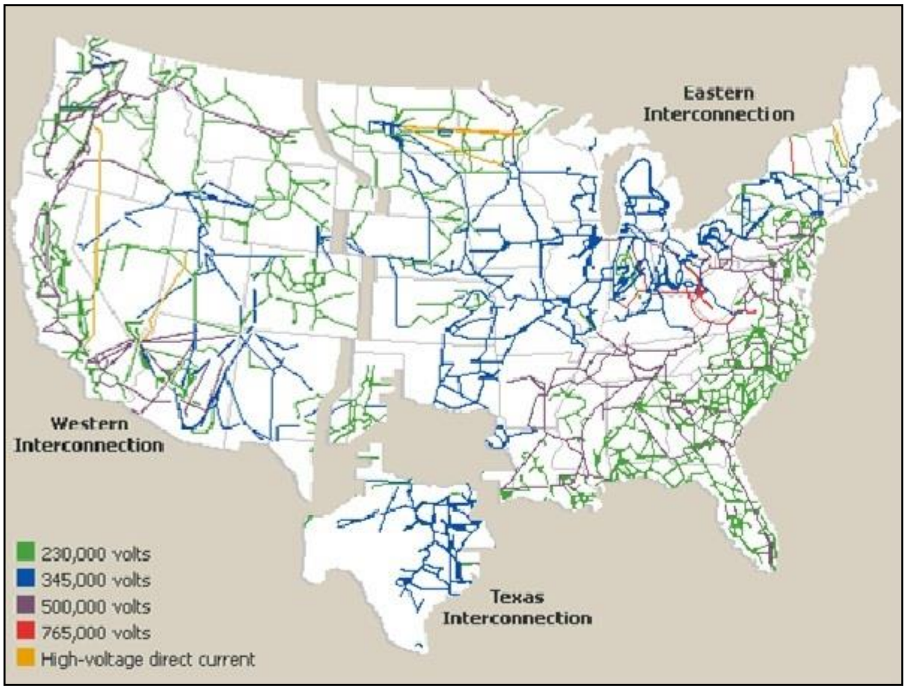


Figure 4B.1 U.S. Electric Power Systems

Each of the three interconnections are designed to have systems of connections between individual utilities to allow for the transfer of power from one network to another to maximize coordination and planning that ensures system reliability.

Transmission System Ownership

Who owns the electric power transmission? As with generation and distribution, many organizations and entities have owners of different parts of the transmission system.

The United States transmission system is essentially co-owned by many groups and entities. Transmission ownership can be categorized in the following groups:

- **Fully-Integrated, Investor-Owned Utilities**—entities that have ownership of generating plants, transmission systems, and distribution systems
- **Transmission/Distribution Owners**—entities that only have ownership of transmission and distribution systems (no generating plants)
- **Transmission Owners**—entities that only have ownership of transmission systems (no distribution or generating plants)

- **Miscellaneous**—other miscellaneous groups such as consumer-owned or publicly-owned companies have varying ownership structures and may even pool their resources to jointly create larger organizations

Of the approximately 200,000 miles of transmission lines that are in the U.S., about 80 percent are owned by investor-owned utilities. The other 20 percent are owned by miscellaneous entities such as state and federal agencies, cooperatives, municipalities, and other regional entities.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Did you know?

Your Electric Bill

The cost of electricity transmission, in comparison to generation and distribution, is comparatively low.

In a typical electric bill, transmission only represents about 10 percent of a customer's electric bill. Distribution accounts for about 28 percent, and generation accounts for about 62 percent.

U.S. Energy Information Administration, 2015

Transmission System Governance

As a result of the 1965 **Blackout** of the East Coast that affected 30 million people, the industry formed the **North American Electric Reliability Council** (NERC). Following the passage of the Energy Policy Act of 2005, the NERC acronym was adopted and NERC became the compliance and enforcement arm of the **Federal Energy Regulatory Commission** (FERC). The overall reliability and coordination of national interconnected power systems, including assessment of transmission systems, are the responsibility of NERC.

NERC's major areas of responsibility:

- Developing, monitoring, and enforcing standards
- Providing education and training
- Analysis and assessment of system operations, including disturbances and failures

Focus on ...

A Strong Transmission System:

- Improves the reliability of the electric power system.
- Gives customers flexibility to diversify the mix of fuels that produces their electricity by increasing generation access.
- Enables competition among power utilities by giving more generation plants access to more markets.

The National Council on Electricity Policy, 2004

Within the regional entities, there are typically multiple **balancing authorities** that operate control centers, which monitor the national grid. Balancing authority operators are responsible for maintaining the load/interchange/generation balance within the control area.

Independent System Operators

Independent system operators (ISOs) were formed under the authority of the Federal Energy Regulatory Commission (FERC) as a way to provide nondiscriminatory access to transmission.

ISOs are nonprofit organizations that combine the transmission capabilities of multiple transmission providers into a single transmission system that can be accessed by many other energy entities. By combining transmission capabilities into one equally accessed system, ISOs can ensure unbiased transmission service. ISOs coordinate, control, and monitor the operation of the electric power system in their respective geographical area.

Regional Transmission Organizations

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The transmission system is part of a regulated delivery system. As mentioned in Module 1, **regional transmission organizations** (RTOs) were formed under the authority of FERC to encourage transmission-owning utilities to turn over control of transmission systems to RTOs. RTOs coordinate, control, and monitor the operation of the transmission grid in their respective geographical area. RTOs provide equal access to the electric transmission network. RTOs differ from ISOs in that they are required to meet specific FERC regulations.

Transmission System Control

The North American Electric Reliability Council enforces standards and guidelines that regulate transmission grid stability. Transmission control centers have monitoring and control systems that are monitored by staff 24 hours a day, 365 days a year. These control-center operation staff members are responsible for **load balancing**, supervising levels of power generation and demand, monitoring the flow of electricity over transmission lines, and maintaining system stability and reliability.

Transmission system controllers and planners constantly analyze the transmission network, searching for problems or irregularities. They assess transmission issues and address problems to maintain the system.

Control systems such as the **Supervisory Control and Data Acquisition System** (SCADA) collect and use automated data to monitor the movement of electricity from their source at generation plants through transmission and distribution lines.

☼ Career Profile: Power System Dispatcher

Brady K. is a power system dispatcher who works for a utility company. Brady says, “I’m responsible for the safe and reliable dispatch of power within a large transmission system. It’s my job to monitor and troubleshoot system voltages and power flows, perform switching activities, and maintain power system configurations, in addition to many other tasks that keep the transmission system running smoothly.”

Dispatchers typically work in large control rooms where they can monitor and control distribution equipment and evaluate readings on computers and other data-providing equipment. Dispatchers monitor and operate equipment such as current converters, voltage transformers, and circuit breakers. Brady says, “I have to stay on my toes at all times. I have to constantly assess and evaluate real-time data and anticipate any changes in the system that might require an adjustment to the grid’s transmission activity.”

Dispatchers control the flow of electricity through transmission lines to substations that supply residential and commercial needs for electricity. It is important for system dispatchers to communicate closely with power plant operators, energy traders, and local utilities to route energy from its source at power-generating plants to the customer.

Brady has an Associate’s degree in electrical power technology. Brady was selected by the utility company he works for to receive extensive on-the-job training and additional classroom instruction to become a system dispatcher.

Brady is required to participate in continuing education to maintain proficiency at his job. Brady says, “Continuing education for my job is fun. We get to do our training using computer simulators. These simulators are designed to replicate a variety of power dispatch situations that could occur in real life.”

Transmission System Security and Reliability

Transmission system security and reliability ensure system integrity. The national transmission system must maintain proper and sufficient operations in order to provide a safe and adequate electrical power supply. Even if certain components fail, the system is designed to continue operations through alternate routes. Redundancy in transmission resources (in addition to generation resources) helps to ensure an availability of resources needed to maintain a functional system.

Transmission Outages

The transmission grid consists of redundant interconnections for transmission lines to help ensure adequate and reliable power to consumers. If one transmission line is out of service due to maintenance, repairs, or other factors, electrical power is rerouted through other transmission lines to continue on its path. However, sometimes the extra load placed on transmission lines can lead to overloads and subsequent outages. This is not a very common occurrence as most transmission systems are designed with the adequate capacity to meet backup needs.

Blackout

A blackout is a total loss of electrical power service in a given area. Blackouts may last from a few minutes to weeks in more severe cases. Blackouts are typically caused by equipment/systems failures or weather-related complications.

A **rolling blackout** is typically a controlled series of interruptions of electrical power service. A rolling blackout involves the process of **load shedding** in which preselected power demand is removed from the power system to help maintain system integrity. While a rolling blackout is usually a preplanned outage, there is usually not much—if any—advance notice.

Rolling blackouts are a last-resort measure used to prevent a total blackout of an electrical power system. Rolling blackouts may be instigated in response to a situation where the demand for electricity exceeds the power supply capability of the network. Rolling blackouts are typically caused by insufficient generation capacity (high-load demand) or inadequate transmission infrastructure.

Brownout

A **brownout** is a partial, temporary reduction in electric power service. During a brownout, the electrical power supply is never totally lost, there is just a decrease in the system's voltage. Brownouts are usually deliberate and controlled events that are used to prevent complete system failure.

Scheduled Outages

A **scheduled outage** occurs when a portion of a power system is shut down intentionally. Scheduled outages differ from other power outages in that they are usually planned and announced well in advance. Scheduled transmission line outages are typically preplanned for activities such as routine maintenance, improvements, or repair. Transmission system construction or maintenance can be especially difficult or impossible during peak customer load periods. This has resulted in some energy electrical-delivery utilities to develop work practices and technical skills of associates to maintain transmission lines and associated circuits while they remain in service carrying energy to customers.

Emerging Technologies

Power delivery systems are a large financial investment for a utility provider. High consumer demand for power coupled with utility companies' common budget restrictions are putting our current transmission system to the test.

With rising power demands and areas of transmission bottlenecking, emerging technologies are being sought to keep the power grid working efficiently and smoothly. Overall use of the transmission system is growing, and new technologies, new construction, and upgrades will be needed to maintain system integrity.

There are currently two main areas of research in transmission technology—new equipment and materials that can improve electricity transmission and new systems for more accurate and efficient management of electricity transmission. Most new transmission technologies involve research on new conductor materials that can increase the amount of power that travels through transmission systems, as well as devices with advanced power-control capabilities.

Focus on ...

Advanced Transmission Technologies

High-Temperature Superconducting Cables: conductors with low-resistance and high-power carrying capability.

Advanced Composite Material Conductors: new conductor cable materials reduce the sagging associated with high temperatures caused by power flowing through the lines.

Equipment Technology

Redundant Lines

Redundancy is a common term with regard to the electric power system. Creating redundant sources of power and redundant routes of power help to ensure the reliable delivery of electricity to consumers. Many transmission systems have redundant lines to serve as a backup in the event of a malfunction or failure.

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Conductors

There are a variety of different designs of conductor cables made of varying materials. Emerging technologies in transmission conductor cables are working to reduce line loss and line faults and overall improvement of efficiency. New **high temperature superconducting (HTS)** technologies and new types of composite conductor materials are being incorporated with the goal of better strength at high temperatures with minimal line losses.

High-temperature superconducting technologies are designed to carry many times the amount of power carried by traditional lines of comparable size. However, these lines require special cooling systems, which are considered a drawback.

As mentioned earlier, typical transmission line conductors are composed of steel and aluminum. New types of composite conductor materials are being explored. New conductors with cores made from composite materials are being designed to reduce line sag.

Monitoring and Control Technology

Automated Line Switching

Transmission systems can be equipped with special automatic-line-switch control systems that allow for automated transmission line switching. When transmission line problems occur, automated line switching systems can minimize the length of service disruptions and help improve system reliability.

Source: America.gov

Real-Time Data

Special systems can be installed that can collect and relay real-time data. Specific data regarding transmission line performance indicators such as line tension, line sag, or temperature can be relayed to control stations for immediate and intuitive automated responses.

Flexible AC Transmission Systems (FACTS)

Flexible AC Transmission Systems (FACTS) are transmission systems that use specialized equipment and systems that provide control of bulk power flow. The benefits of using FACTS technology include increased transmission and transfer capability and control of power flow and voltage.

Smart Grid

Of all the emerging technologies aimed at the improvement of the electric power system, perhaps the most commonly recognized emerging electric power and transmission technology is what is called the "**smart grid**." The emerging technologies mentioned above, in addition to others, are being collectively pooled together to develop the potential to create a dynamic and reactive "smart" power grid system.

The concept of the smart grid is envisioned as a dynamic and interoperable system involving the entire national electricity grid that delivers accurate and useful information and control options for customers, distributors, and grid operators, for the purpose of collectively reducing system demands and costs, detecting and intuitively fixing problems, and increasing energy efficiency.

Focus on ...

Smart Grid–Key Components

- Reliable
- Secure
- Efficient
- Flexible
- Responsive
- Intuitive

The government has pledged funds to aid in the creation of the smart grid, and the transformation of the current system has already begun. It is estimated that the full smart grid transformation will take 20 to 25 years.

Focus on ...

Smart Grid Vision

- Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid
- Dynamic optimization of grid operations and resources, with full cybersecurity
- Deployment and integration of distributed resources and generation, including renewable resources
- Development and incorporation of demand response, demand-side resources, and energy-efficiency resources
- Deployment of "smart" technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation
- Integration of "smart" appliances and consumer devices
- Provision to consumers of timely information and control options
- Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid

SmartGrid.gov, 2011

The Smart Grid and Transmission

The new smart grid will affect all parts of the national electricity system including generation, transmission, and distribution.

Smart grid technology provides many possible benefits for the electric power transmission system. Smart grid technology will enable transmission system operators to receive special data and communications regarding consumer energy use and system performance. This improved system knowledge will help operators and customers better manage the efficient use of electricity.

Focus on ...

Smart Grid and Transmission

- More efficient transmission
- Quicker system restoration following disturbances
- Improved security

SmartGrid.gov, 2011

Improved sensing and measurement technologies coupled with improved management interfaces will help transmission operators to better detect and isolate outages and perform rapid diagnostics that aid in quick and accurate decision-making.

While renewable energy development has created additional sources of power generation, often they are located far away from existing transmission lines. Smart grid technology is envisioned to provide a flexible transmission framework that would better integrate and accommodate new renewable energy generation sources.

Module 5 will cover the effects of smart-grid technology on electric power distribution.

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Unit B Glossary

balancing authorities—regional organizations responsible for planning for and maintaining the balance of electricity resources and electricity demand

blackout—power loss affecting many consumers over a large geographical area for a significant period of time

brownout—a planned partial reduction in the voltage of electrical power service

Federal Energy Regulatory Commission (FERC)—an independent regulatory agency within the Department of Energy and the successor to the Federal Power Commission; it governs interstate electricity sales, wholesale electric rates, hydroelectric licensing, natural gas pricing, oil pipeline rates, and gas pipeline certification

high temperature superconducting (HTS)—a technology for transmitting electricity that uses special conductors designed to improve transmission capabilities

independent system operators (ISOs)—created under the authority of FERC; designed to administer the transmission grid on a regional basis in a neutral manner

load balancing—meeting fluctuations in demand or matching generation to load to keep the electrical system in balance

load shedding—process by which an electric utility removes power demand from a power system (cuts electricity to certain customers) to maintain system integrity

North American Electric Reliability Corporation (NERC)—formed in 1968 in response to the 1965 blackout, NERC is the electric reliability organization certified by the Federal Energy Regulatory Commission to establish and enforce reliability standards for the bulk-power system; all bulk-power system owners, operators, and users are required to register with NERC

regional transmission organizations (RTOs)—created under the authority of FERC; designed to administer the transmission grid on a regional basis in a neutral manner; FERC stated that entities desiring to be qualified as RTOs must first meet a specific list of characteristics and functions

rolling blackout—a controlled, temporary interruption of electrical power service; typically imposed by a utility over portions of a service area to meet heavy demand and when there is a deficiency in the supply of power

scheduled outage—when a portion of a power system is intentionally shut down, usually to allow for maintenance or other preplanned activities

smart grid—modernization of the current grid technology; has the ability to monitor energy flow and communicate data back to utility companies; use of smart meters; distributed generation allowing smaller power sources to feed energy back into the grid, store energy generated in off-peak hours, and distribute it during peak hours

Supervisory Control and Data Acquisition (SCADA)—a system of remote assessments used to monitor and control the electric transmission system

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