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HIGH-VOLTAGE ELECTRIC POWER SUBSTATION CONFIGURATION INFRASTRUCTURE SYSTEM OVERVIEW

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This Infrastructure System Overview details the three types of electric power substations and the functions they perform as part of the bulk power system (BPS). A broad overview of the BPS, substation functions, and substation components is also provided. This product focuses on energy transmission exceeding 100,000 volts. This product provides the reader a primer on the role of substations in transmitting electricity between the generating station and the consumer.

SCOPE NOTE: This product is intended for individuals with minimal knowledge of the BPS, the components of BPS and their functions. This product does not describe threats, vulnerabilities, or consequences of any aspect of the infrastructure system.

The U.S. Department of Homeland Security (DHS)/Office of Cyber and Infrastructure Analysis (OCIA) coordinated this product with the DHS/National Protection and Programs Directorate/Office of Infrastructure Protection/Sector Outreach and Programs Division/Electricity Subsector and the U.S. Department of Energy/Office of Electricity Delivery and Energy Reliability.

BACKGROUND

The U.S. electric BPS, or high-voltage (HV) network, transmits electricity voltages exceeding 100 kilovolts (kV) and is designed to transport sufficient HV electricity from the point of generation across the electric grid to local utility distribution networks and consumers. The BPS is comprised of approximately 47,000 substations operating at or above 100 kV.[1] Figure 1 displays the transmission portion of the BPS accounting for more than 240,000 miles of transmission lines operating at 230 kV and above.[2]

[1] U.S. Department of Homeland Security (DHS). (2017). Homeland Infrastructure Foundation-Level Data. https://hifld-dhs-gii.opendata.arcgis.com/datasets/143c1a29fd184b709e86b343ebcb2614_0?uiTab=table. Electric Substations – Table. Accessed July 31, 2017.
[2] DOE. (2017). Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review. https://energy.gov/sites/prod/files/2017/02/f34/Appendix--Electricity%20System%20Overview.pdf. p. A-7. Accessed May 11, 2017.

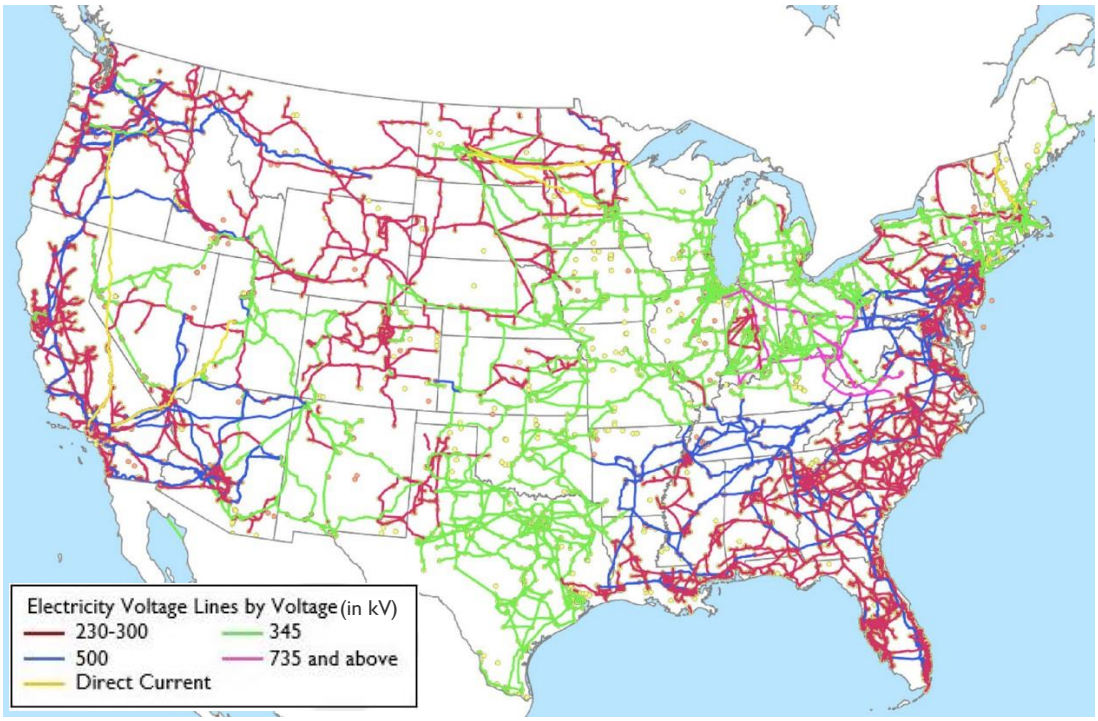

FIGURE 1—HIGH-VOLTAGE TRANSMISSION NETWORK OF THE 48 CONTIGUOUS STATES AS OF 2015[3]

The U.S. BPS comprises three distinct power grids, also called interconnections. These three interconnections manage and operate their grid largely independently from each other.[4] Electric utilities within each interconnection are electrically tied together. The Eastern Interconnection includes the eastern two-thirds of the continental United States and Canada from the Great Plains to the eastern seaboard. The Western Interconnection includes the western one-third of the continental United States, the Canadian provinces of Alberta and British Columbia, and a portion of Baja California Norte in Mexico. The Electric Reliability Council of Texas (ERCOT) Interconnection comprises most of the State of Texas (figure 2).[5]

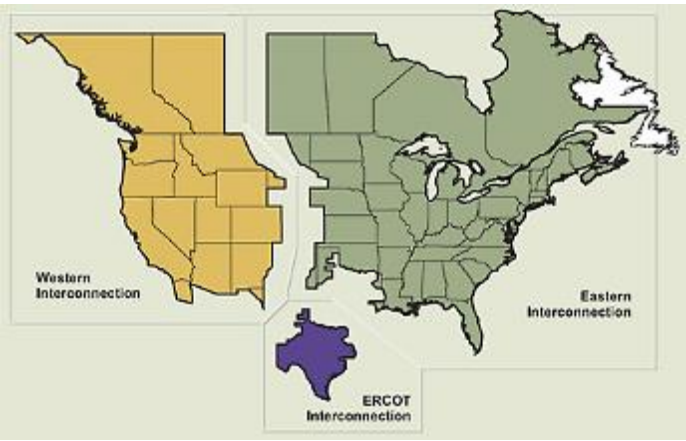

FIGURE 2—NORTH AMERICAN POWER INTERCONNECTIONS[6]

[3] DOE. (2017). Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review. https://energy.gov/sites/prod/files/2017/02/f34/Appendix--Electricity%20System%20Overview.pdf. p. A-8. Accessed May 11, 2017.
[4] EIA. (2016). U.S. electric system is made up of interconnections and balancing authorities. https://www.eia.gov/todayinenergy/detail.php?id=27152. Accessed October 30, 2017.
[5] DOE. (2017). Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review. https://energy.gov/sites/prod/files/2017/02/f34/Appendix--Electricity%20System%20Overview.pdf. p. A-30. Accessed May 11, 2017.
[6] The National Academies Press. (2009). "America's Energy Future: Technology and Transformation. https://www.nap.edu/read/12091/chapter/13#567. p. 568. Accessed May 11, 2017.

Within the interconnections, Federal Energy Regulatory Commission (FERC) established rules to create voluntary, non-profit, independent system operators (ISOs) and regional transmission organizations (RTOs) to control electric grids ranging in size from single to multiple states. There are currently seven ISO/RTOs (figure 3) in the United States and their geographic coverage and membership changes periodically.[7] Most of the states in the Western Interconnection and the Southeast United States have not adopted the ISO/RTO model.

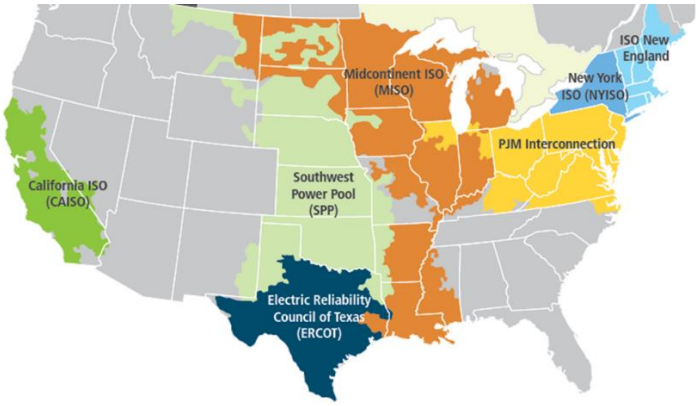

FIGURE 3—REGIONAL TRANSMISSION ORGANIZATIONS[8]

ISOs and RTOs administer the regional wholesale electricity markets that enable participants to buy and sell electricity on a day-ahead or a real-time spot market, daily integrate multiple sources of electricity generated within their region onto the grid including nuclear, natural gas, coal, wind, and solar generation, as well as coordinate the transmission of electricity across the country.[9] In addition to managing regional electric grids, they provide long-term planning for the regional bulk electricity system. RTOs have additional FERC mandated responsibilities to maintain reliability of the grid and coordinate and ensure open and fair access to all eligible customers to the regional electricity transmission network.[10]

The ISOs and RTOs within each interconnection maintain the reliability of the power system by providing multiple routes for power to flow and by allowing producers to supply electricity to multiple distribution networks. The ISOs and RTOs ensure that power demand and supply are finely balanced and maintain the safe and reliable operation of the power grid. Redundancy within the power grid prevents service interruptions, because the ISOs and RTOs can rapidly share and reroute power if a generation plant, substation, or transmission line fails.[11] In areas not covered by ISOs and RTOs, power companies rely on bilateral trade transactions to cover electric shortfalls.[12]

SUBSTATIONS

Substations are responsible for the conversion, transfer, routing, and rerouting of electricity. The majority of substations are unmanned. Unmanned substations communicate their operational status to a distant manned control center where personnel monitor, interact with, and control substation equipment. Within the substation is a control building containing the equipment to monitor, control, and communicate the status of substation

[7] EIA. (2011). About 60% of the U.S. electric power supply is managed by RTOs. https://www.eia.gov/todayinenergy/detail.php?id=790. Accessed October 31, 2017.
[8] DOE. (2017). Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review. https://energy.gov/sites/prod/files/2017/02/f34/Appendix--Electricity%20System%20Overview.pdf. p. A-32. Accessed October 31, 2017.
[9] DOE. (2015). QER Report: Energy Transmission, Storage, and Distribution Infrastructure; Appendix C Electricity. https://energy.gov/sites/prod/files/2015/09/f26/QER_AppendixC_Electricity.pdf. p EL-41.Accessed November 1, 2017.
[10] DOE. (2015). United States Electricity Industry Primer. https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf. pp. 25-26. Accessed May 19, 2017.
[11] U.S. EIA. (2016). U.S. electric system is made up of interconnections and balancing authorities. https://www.eia.gov/todayinenergy/detail.php?id=27152. p. 1. Accessed June 21, 2017.
[12] DOE. (2017). Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review. https://energy.gov/sites/prod/files/2017/02/f34/Appendix--Electricity%20System%20Overview.pdf. p. A-37. Accessed October 31, 2017.

components and flow of power through the substation along with a backup power supply to ensure the equipment continues to function after a loss of electricity.

Three types of BPS substations exist: transmission, switching, and distribution.[13]

- Transmission substations connect power plants to the BPS grid and convert low-voltage electricity to HV.
- Switching substations serve as nodes linking transmission and distribution networks. Without transforming the voltage, they are used to reroute power, switch current to back-up lines, or for parallelizing circuits in case of failure.
- Distribution substations are the point at which electricity is converted from HV to a lower voltage and begins moving to end-use customers.

Figure 4 displays the generating station with the transmission, switching, and distribution substations and the distribution network.

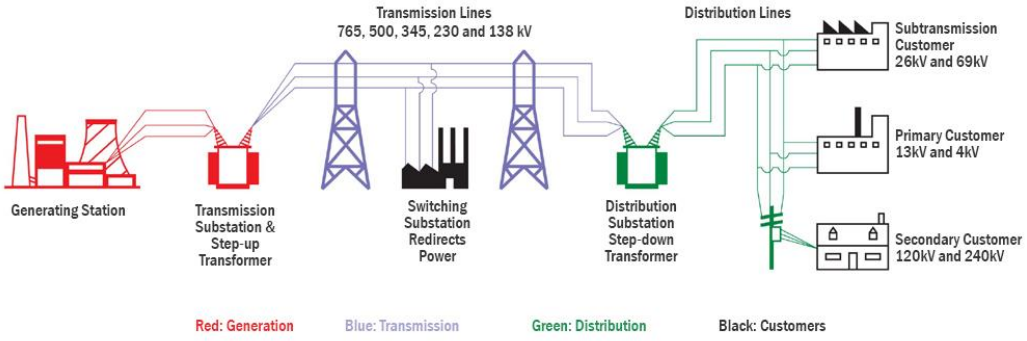

FIGURE 4—THE ELECTRIC GRID[14]

Transmission Substations

The electricity produced in a generating station is considered low voltage, usually less than 35 kV and is transported over a power line to a nearby transmission substation.[15] At the transmission substation, the electric voltage is increased by step-up transformers in order to increase efficiency and reduce electricity loss during transmission across the BPS grid.[16]

FIGURE 5—HIGH-VOLTAGE TRANSFORMER[17]

[13] IEEE. (2017). "Transmission System: The Interconnected Bulk Electric System." p. 66. Accessed May 19, 2017.
[14] DOE. (2015). Modified from the *Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure*. https://energy.gov/sites/prod/files/2015/04/f22/QER-ALL%20FINAL_0.pdf. p. 3-3. Accessed May 15, 2017.
[15] DOE. (2015). United States Electricity Industry Primer https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf. p. 15. Accessed May 19, 2017.
[16] DOE. (2012). "Large Power Transformers and the U.S. Electric Grid." https://energy.gov/sites/prod/files/Large%20Power%20Transformer%20Study%20-%20June%202012_0.pdf. p. 5. Accessed November 1, 2017.
[17] Jakit17. (nd)."High Voltage Transformer." https://Shutterstock.com. Accessed November 8, 2017.

Step-up transformers (figure 5) convert the low voltage to a higher voltage ranging between 115 kV and 765 kV.[18] These transformers increase voltage by creating a magnetic field between a smaller and a larger metal coil, and a process called electromagnetic induction which creates the HV current from the low generation plant voltage. After the voltage is increased, the electricity moves from the transmission substation to the transmission power lines.

Switching Substations

Switching substations are located between transmission and distribution substations to redirect power, but do not increase or decrease the voltage.[19] Switching substations generally route higher voltage, such as 138 kV or 230 kV, to a city or to industrial customers for their processes.

An essential function performed by a switching substation is the connecting and disconnecting of transmission lines or other components to and from the grid. An event requiring switching may be planned or unplanned; such as a transmission line requiring maintenance may need to be de-energized.

Distribution Substations

Distribution substations are located at the end of the BPS transmission circuit. Within the distribution network, multiple distribution substations could step down the voltage and route electricity; or, multiple transformers could operate in a substation. Distribution substations use step-down transformers to decrease voltage. Step-down transformers reduce voltage by creating a magnetic field between a larger and a smaller metal coil, and through electromagnetic induction produce a lower voltage. Electricity leaving the distribution substation is medium-range voltage (34–69 kV) or less.[20]

This medium-range voltage, moving on the primary distribution circuits, is the beginning of the distribution network to customers. As the electricity moves closer to the customers, it passes through additional distribution transformers further reducing the voltage. Finally, the electricity passes through a neighborhood distribution transformer, usually a cylindrical device on a telephone pole or on a concrete pad, producing the 120/240 service voltage used by a business or a household consumer.[21]

SUBSTATION EQUIPMENT

HV substations can contain a large amount of equipment to increase or decrease voltage, route electricity, monitor activity, and ensure safety.[22,23] Most substations are unmanned and require a significant amount of information technology and communications equipment to perform efficiently and safely and allow monitoring by manned control centers. Figure 6 displays the component of a generic substation and how electric power moves through the substation.

[18] DOE. (2015). United States Electricity Industry Primer. https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf. Figure 15, p. 15. Accessed May 19, 2017.
[19] Oak Ridge National Laboratory. (2015). "Opportunities for Energy Efficiency Improvements in the U.S. Electricity Transmission and Distribution System." https://energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20Opportunities%20for%20Energy%20Efficiency%20Improvements%20in%20the%20US%20Electricity%20Transmission%20and%20Distribution%20System_0.pdf . p. 9. Accessed November 1, 2017.
[20] DOE. (2015). United States Electricity Industry Primer. https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf. p 15-16. Accessed May 19, 2017.
[21] Bright Hub Engineering. (2010). "How a Substation Works." http://www.brighthubengineering.com/power-generation-distribution/71084-how-a-substation-works/. Accessed May 18, 2017.
[22] OSHA. (2010). Electric Power Generation Transmission Distribution eTool. https://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/substation.html#Step-up. Accessed May 18, 2017.
[23] Bright Hub Engineering. (2010). "How a Substation Works." http://www.brighthubengineering.com/power-generation-distribution/71084-how-a-substation-works/. Accessed May 22, 2017.

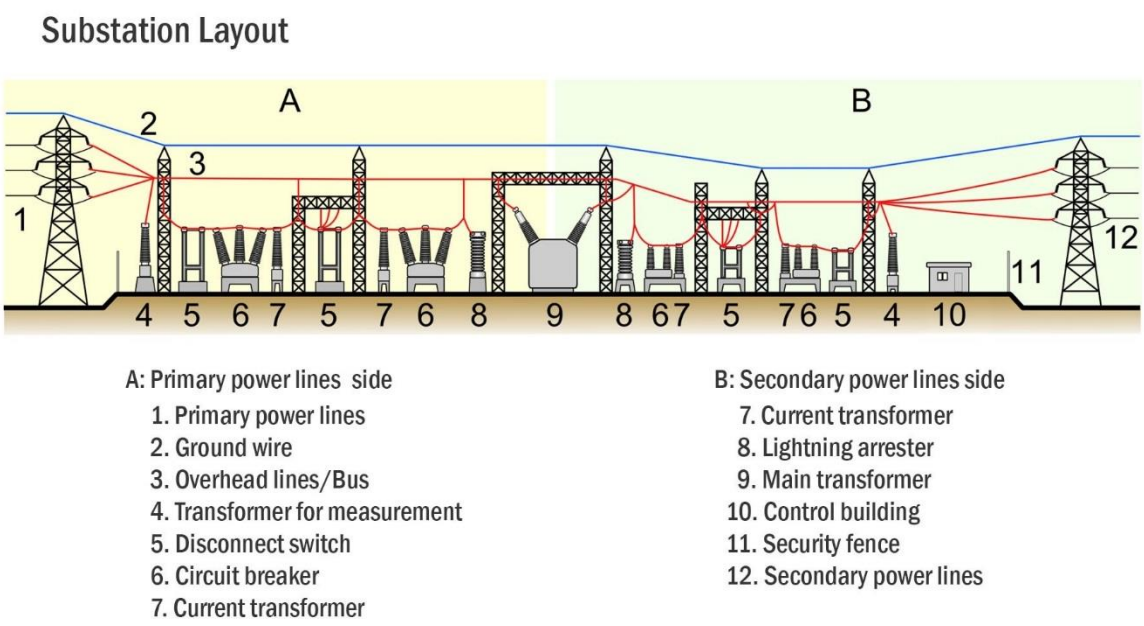

FIGURE 6—TRANSMISSION AND DISTRIBUTION SUBSTATION LAYOUT[24]

A bus system (figure 7) is a solid copper conductor that transfers electricity from the line and moves electricity within the substation. Transformers receive electricity from the bus system, increase or decrease the voltage, and send it out on another bus system. Circuit breakers and disconnect switches are usually found where the bus system and transmission line connect. Circuit breakers are designed to automatically halt the flow of electricity when a fault occurs to ensure equipment in the substation is not damaged and to halt the flow of electricity to the fault location for safety. Disconnect switches, unlike circuit breakers, are manually activated to halt the flow of electricity to a piece or a bay of equipment in the substation to allow the safe conduct of maintenance by ensuring no power moves through the equipment when the switch is opened. Ground wires and lightning arresters protect the equipment from lightning while the fence provides security for the equipment.

FIGURE 7—SUBSTATION BUS BARS[25]

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[24] Electrical Voice. (August 19, 2017) "Components of a Substation." https://electricalvoice.com/components-substation/. Accessed November 17, 2017.
[25] Chaiya. (nd)."Bus bar, supporting and Equipment in Switchgear." https://Shutterstock.com. Accessed November 17, 2017.

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