D.1 – Electrical System Overview

ELECTRICAL SYSTEM OVERVIEW

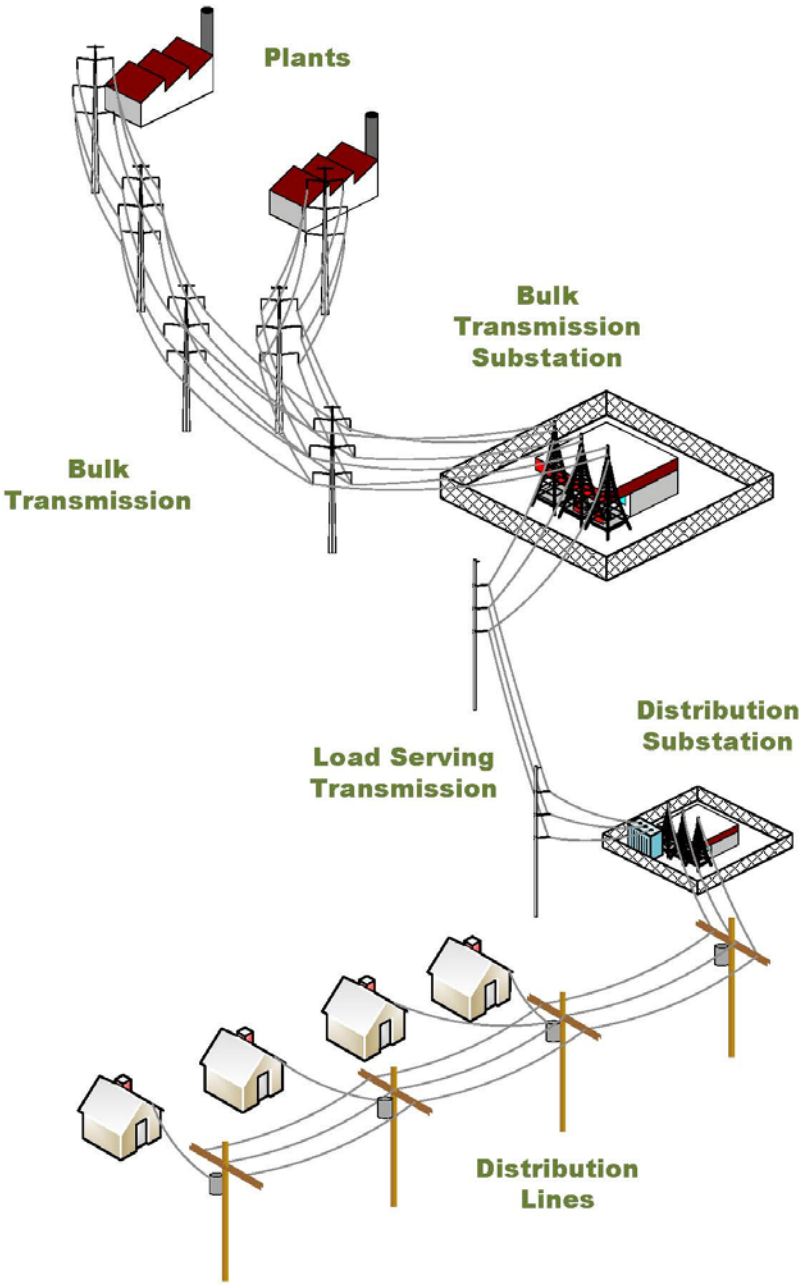
When a customer turns on a light switch, a circuit is completed that connects the light bulb with the wires that serve the customer's building. The building wires are connected to a transformer and a distribution line outside of the building. The distribution lines, in turn, are connected to substations and through larger transformers to transmission lines, which are connected to the bulk-power transportation system that carries electricity from electric generating plants to the areas where the electricity is needed.

Electricity is produced at both large and small generating plants. Electricity can be generated using a variety of sources or fuels, including solar, wind, and hydro; internal and external combustion of biomass, biofuels, natural gas, and coal; and heat and steam created through nuclear fission. Regardless of the fuel used, electricity is produced by converting the fuel's energy into electric energy through the use of a generator that converts mechanical energy into electric energy. Electric energy is generated at a specific voltage and frequency. For it to be useful, electricity must be transmitted from the generation source to consumers. Unlike other products or services, electricity must be generated instantaneously with its consumption, so generators connected to the system must adjust their electric output to respond to changes in customer demand. The transmission system must also be able to accommodate changes in both generation and consumption.

Typically, the voltage of electricity generated in a power plant is increased (stepped-up) by transformers installed close to the generating plant. The electricity is then transported over transmission lines, often at voltages in excess of one hundred thousand volts (*e.g.*, 115 kV, 230 kV, 345 kV). The reason for stepping up the voltage is that it is more efficient to move electricity over longer distances at higher voltages because the system experiences fewer electrical losses. Once the electricity reaches the locality where it will be consumed, the transmission voltage (*e.g.*, 69 kV and higher) is reduced (stepped-down) to voltage appropriate for distribution to end use customers by transformers at a distribution substation facility. The electricity is then further transformed and distributed at distribution "primary" voltages (*e.g.*, 13.8 kV) within communities by the distribution system which delivers power for individual customer use.

A schematic showing the transfer of electricity from generator to consumer is shown below in Figure 1.

Figure 1: Electrical System



Note: Figure 1 is an artistic portrayal of an electrical system and is not a true representation of all actual electrical system components.

TRANSMISSION SYSTEM OVERVIEW

The transmission system is made up of high voltage transmission lines which can carry electricity long distances. The transmission system is designed to be an integrated system that is able to withstand the outage of a single transmission line without major disruption to the overall power supply. The majority of the bulk transmission facilities consist of transmission lines and bulk transformers at 100 kilovolt ("kV") and above.

HIGH VOLTAGE TRANSMISSION LINES

Transmission lines are made up of conductors, which are bundled groups of wires usually made from copper or aluminum, that are usually held up by poles or towers that are made from wood or steel.

Transmission lines carry electricity from the generation source to the area where the power is needed. Electricity is simply the movement of electrons within a conductor (the wire). The rate at which electricity moves through a wire is called current and is measured in amperes (or amps). The force that moves the electricity through the wire is called voltage. Voltage is measured in terms of volts or kilovolts ("kV"). One kilovolt equals 1,000 volts. The wire conducting the current offers resistance to its movement. This resistance is measured in a unit called ohms. As expected, the higher the resistance in the conductor, the slower the rate of flow (the lower the current). Some materials are better conductors than others, *i.e.*, they offer less resistance. The wires used by utilities to conduct electricity are usually made of copper or aluminum, which conduct electricity with relatively little resistance.

TRANSMISSION SUBSTATIONS

Substations contain equipment that allow transmission lines to connect with one another, or allow power to be changed to a lower voltage for distribution, typically 34.5 kV and below. The equipment inside a substation includes breakers, transformers, switches, buses, and relays. Breakers protect lines by stopping power from flowing down a line when the line experiences a fault (such as a lightning strike). Transformers increase voltage to move power over longer distances more efficiently or decrease voltage for consumer use. Switches isolate pieces of equipment in a substation to allow for maintenance or to configure the power system. A bus is a substation conductor, usually aluminum or copper, that moves the power through the substation among the lines that connect within the substation. Relays are programmed to sense the flows within the substation and on the lines that connect to the substation. Relays are capable of detecting system conditions that are abnormal and opening lines to respond. New substations are generally designed to have room for future growth, and substation equipment is generally designed so as not to limit the capacity of any transmission lines on the system.

DISTRIBUTION SYSTEM OVERVIEW

The distribution system is made up of substations which house transformers and distribution feeder circuits that provide the path for delivering electrical energy from the distribution substation to the distribution customer transformer. Distribution feeder circuits for standard service to customers are designed as radial circuits, so the failure of any single critical element of the feeder circuit causes a customer outage, which is an allowed outcome for a distribution system unlike for a transmission system. Generally, the distribution system is planned to facilitate single-contingency switching to restore outages within approximately one hour. Feeders are designed to facilitate restoration of mainline capacity and restoration of service to most customers with simple manual field switching with some exceptions. A description of distribution substations and feeder circuits is provided below.

DISTRIBUTION SUBSTATIONS

Distribution substations interconnect transmission line voltages (typically 69 kV and above) to distribution voltage for delivery across a distribution system. The main distribution substation elements are switches, bus, breakers, and distribution substation transformers. Various other equipment is installed for purposes including load monitoring, remote control, electrical problem detection, electrical problem isolation, voltage regulation, and security.

Switches are used to route or reroute flow of electric energy and to isolate substation equipment for safe construction, maintenance, and inspection. Typically distribution feeder switches are operated when electrical load is turned off. Switches are used to reconfigure the electric delivery system for maintenance and during contingency operation.

Bus are electrical conductor(s) that provide both a path for electrical energy flow and multiple connection points for electrical devices including switches, transformers, and breakers. They provide the multiple paths for electrical energy flow to support normal and contingency operations.

A breaker is a switching device designed to interrupt electrical energy flow between energized elements. Breakers interrupt and quickly isolate electrical energy flow from transmission lines to distribution substation transformers (transformer breakers) and from distribution substation transformers to distribution feeder circuits (feeder breakers).

Distribution substation transformers are the key distribution substation element used by Distribution Planning Engineers when developing plans and options to electrically serve an area of distribution customer load. Other substation equipment is selected and installed based on the transformer quantity and size planned in the ultimate substation design. The maximum number and size of substation transformers in the ultimate substation design are the primary limiting factors for the amount of electrical energy that a substation can deliver.

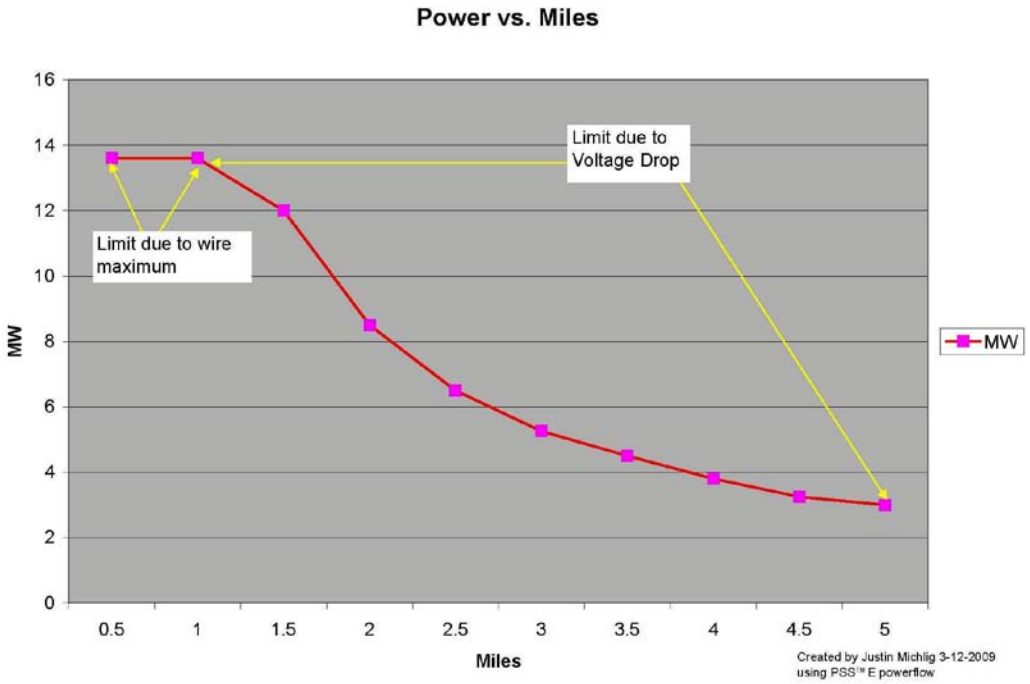
Xcel Energy plans and constructs distribution substations with a physical footprint sized for the ultimate substation design. The maximum ultimate design capacity established in Xcel

Energy planning criteria is three transformers at the same distribution voltage.[1] This maximum size balances substation and feeder circuit costs with customer service considerations including limitations of feeder circuit routes emanating from substations, circuit exposure of long feeder circuits, ease of operation, cost of operation, customer outage restoration, and the electrical losses. Transformers and feeder circuits are incrementally added within the established footprint until the substation is built to ultimate design capacity.

Generally, distribution substations are located as close to the area of heaviest load or electrical usage, as possible. This is because the farther a substation is from the load being served, the longer the feeder circuits emanating from the distribution substation, which impacts the amount of load a feeder circuit can efficiently carry to customers. Figure 2 illustrates how the ability of a distribution feeder line to serve load decreases as the load moves further from the substation along the feeder circuit. This capacity reduction is caused by a reduction in voltage – as the line length increases, the voltage at the end of the line decreases. This is due to electrical and physical properties in the power system. Closest to the substation, a feeder circuit's limit is the maximum amount of current the circuit can carry. At points along the feeder circuit farther away from the substation, the limit becomes the maximum amount of allowable voltage drop. For example, at 2.5 miles from the transformer, the capacity of a feeder is reduced by half. By analogy, a person generally can hold greater weight closer to the person's body and as the weight moves further from the body, the amount of weight that a person can hold straight out decreases. Therefore, when planning the electric distribution delivery system, engineers try to locate distribution substations as close to the major load areas as possible, which decreases the lengths of the feeder circuits serving that load and consequently maintains the ability of those feeder circuits to carry load efficiently.

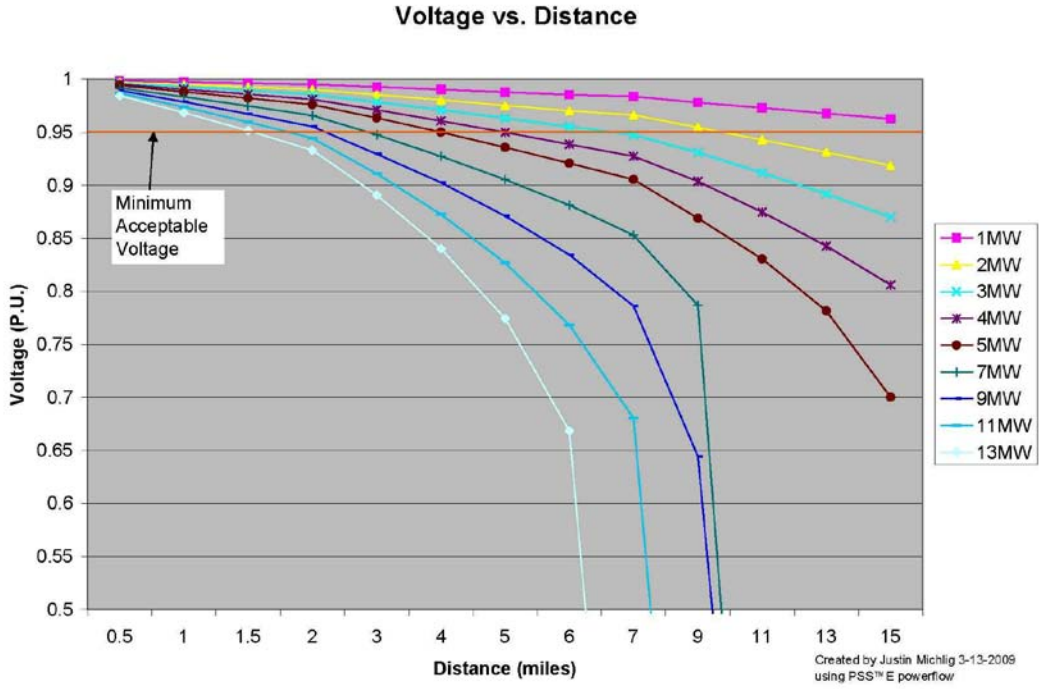
[1] There is one exception to this criterion. In downtown Minneapolis, the Fifth Street Substation houses four transformers to serve the significant load.

Figure 2: Relationship Between Feeder Circuit Load and Length



When feeders circuits traverse a long distance from their sources (*i.e.*, distribution transformers) and serve load the entire length of their lines, then those feeders may experience excessive voltage drop, which can result in unsatisfactory operation of and damage to electrical equipment. Figure 3 shows the relationship between distance and voltage drop on a typical feeder conductor.

Figure 3: Relationship Between Voltage and Distance from Substation Transformer



DISTRIBUTION FEEDER CIRCUITS

The primary distribution feeder circuit elements are the feeder breaker, the feeder circuit main line and the feeder circuit taps.

A feeder breaker is both part of the distribution substation and the beginning of the distribution feeder. The breaker is a piece of equipment located at a substation which, in combination with associated measurement equipment, is capable of detecting, switching, and interrupting the electrical power on a particular feeder under predetermined conditions.

A distribution feeder main line typically begins at the feeder breaker and radially feeds segments of overhead wire or underground cable with switch connections to adjacent feeder circuit main lines. The main line feeder circuit is typically comprised of electrical equipment including overhead wire, underground cable, voltage regulation equipment, and overhead and underground switching devices. The typical feeder circuit main line is capable of delivering all of the electric energy from the feeder breaker to an average of 1,000 distribution customers.

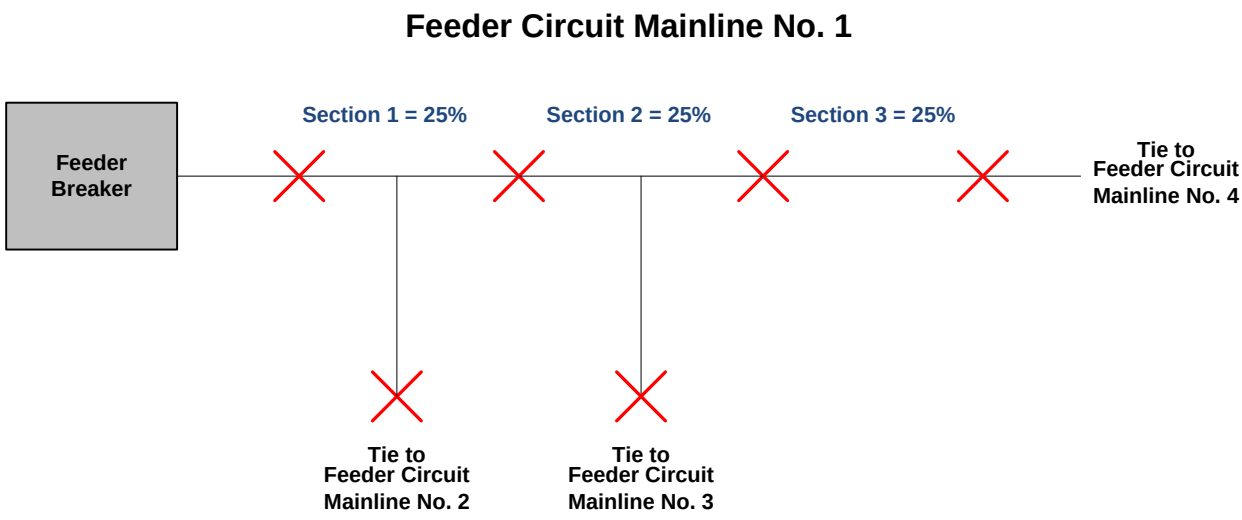
Each distribution main feeder is generally composed of three equal sections that should serve no more than 25% of the total capacity of the main feeder. As a result, during system intact conditions, a feeder circuit with three sections must be loaded to no more than 75% of capacity (also known as utilization rate), which reserves 25% of the capacity to be used to meet the load of an adjacent feeder circuit in the event of a failure.

Main line feeder sections are separated by switches so that each section can be isolated from each other and from the substation breaker to facilitate maintenance of individual pieces of equipment while continuing uninterrupted electric service to distribution customers. Each of the three main line feeder sections is connected to an adjacent feeder so that the entire feeder may be restored by conducting a minimum number of switching operations for rapid restoration of a worst case failure, an outage of the head end element of the feeder circuit.

Feeder circuit taps are fused segments of overhead wire or underground cable connected to and fed from the feeder main line that deliver electrical energy to distribution transformers adjacent to customer locations. Tap fuses, which separate the tap from the main line, operate when an electrical problem occurs downstream of the fuse to isolate the problem from the main line and keep the largest possible number of customers in service at all times.

Figure 4 depicts a feeder circuit, including the breaker, and the three sections of the main feeder, which are separated by switches, each represented by an "X".

Figure 4: Typical Distribution Feeder Circuit Mainline with Three Sections Capable of System Intact N-0 and First Contingency N-1 Operations



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