APPENDIX E

System Protection

Chapter Structure

A. TRANSMISSION SYSTEM PROTECTION

The discussion of transmission line protection begins with the definition of a transmission line. A transmission line is defined by the location of the circuit breakers or other sectionalizing devices that isolate the line from other parts of the system and include sections of bus, overhead conductor, underground cable, and other electrical apparatus that fall between these circuit breakers.

The fundamental concepts of zones of protection and overlapping zones of protection need to be addressed. A protection zone is defined as the area a relay or set of relays are responsible to protect. For a transmission line this zone is normally bounded by the circuit breakers and current transformers (CTs) that connect to the relays at each end of the line. Overlapping zones of protection is the practice of using CTs located in Zone A to provide current inputs to relays protecting Zone B and vice versa, as represented in Figure E-1. Overlapping zones ensure that equipment located at the edges of a zone is protected.[1]

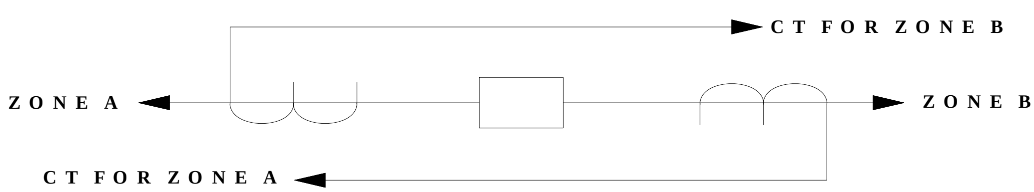

Figure E-1 - Overlapping zones of protection.[2]

One of the more important design considerations in transmission protective relaying is reliability. Relaying reliability included two things: dependability and security. Dependability is defined as

[1] *IEEE Guide for Protective Relay Applications to Transmission Lines*, IEEE Std. C37.113-1999. (1999). New York, NY. IEEE.
[2] *IEEE Guide for Protective Relay Applications to Transmission Lines*, IEEE Std. C37.113-1999. (1999). New York, NY. IEEE.

the degree of certainty that a relay will operate correctly. Security is defined as the degree of certainty that a relay will not operate incorrectly.[3] A balance between dependability and security needs to be reached. Dependability is the easier of the two to obtain by providing redundant relays, fail-safe designs, and thorough testing of protection schemes. Security is harder to obtain, but can be improved through the use of high quality equipment, self-checking relays, and avoiding overly complicated protection schemes.

Standard transmission line protection methods may include phase overcurrent, ground overcurrent, phase distance, ground distance, and pilot system relaying. Overcurrent protection (phase and ground) on transmission lines is often controlled by a directional element that determines which direction current on the system is flowing in order to distinguish between faults within a zone of protection as opposed to an external fault. This selectivity is important to ensure only the faulted section of the line is isolated, allowing the rest of the system to operate normally. Over current protection must be used carefully as it may create coordination issues with other protection devices or schemes. Coordination and selectivity determine the ability of a protection scheme to distinguish where a fault is in the system and then take action in the proper sequence to remove the faulted line without isolating more of the transmission system than is necessary.[4] As line lengths increase and more zones of protection are added, coordinating between the many zones becomes difficult.

Distance relaying (phase and ground) is commonly used in transmission line protection. It is capable of approximately determining the location of a fault and determining if the fault is within the relay's zone of protection. During a fault, the distance relays determine the fault location by measuring voltage and current to calculate the apparent impedance to the point of the fault and then compare it to the fixed impedance of the transmission line. Since the relay is calculating the apparent transmission line impedance there may be some error. Therefore, the standard practice for setting distance relays is to set a zone 1 to trip instantaneously if a fault occurs within 80-90% of the transmission line length, and zone 2 is set to trip with some time delay if a fault occurs within120% of the line length. Standard distance relaying allows for easy coordination between transmission line sections, but does not allow for high speed tripping on the entire line. The delays necessary for coordination may result in greater damage to the line during a fault than if the whole line could be tripped instantaneously for any fault along the line. Further complicating the use of distance relaying are multi-terminal and tapped transmission lines which can affect the apparent impedance of the line due to network changes.[5]

[3] *IEEE Guide for Protective Relay Applications to Transmission Lines*, IEEE Std. C37.113-1999. (1999). New York, NY. IEEE.
[4] *IEEE Guide for Protective Relay Applications to Transmission Lines*, IEEE Std. C37.113-1999. (1999). New York, NY. IEEE.
[5] *IEEE Guide for Protective Relay Applications to Transmission Lines*, IEEE Std. C37.113-1999. (1999). New York, NY. IEEE.

To provide high speed tripping on 100% of the protected line, pilot schemes are used. Pilot schemes use communications channels to transmit information between the local and remote relay terminals. The communication method used may be power line carrier, which transmits a high frequency signal on one or more of the transmission line conductors, standard telephone lines, or fiber optic cables. The two most common classes of pilot schemes are directional comparison, and current comparison or line differential. The directional comparison schemes use fault current direction information transmitted between the two terminal relays to determine the fault location. The current comparison schemes compare the currents at each end of the transmission line. The two currents should normally be nearly equal. If the difference between the measured currents at each terminal is too great, the relays determine that a fault has occurred and act to remove the fault from the line. The advantage of these types of schemes is they remove the line from service when a problem occurs without delay or loss of security.

The use of automatic reclosing of breakers to restore service prevents long outages due to temporary faults such as tree contacts or lightning strikes[6]. If a breaker trips open, a timer will reclose the breaker after a short period of time. If the fault has disappeared the breaker will stay closed and the customers affected will see no further interruption of power. If the fault still exists after reclosing, the breaker will once again trip. If this occurs a preset number of times, the breaker will no longer attempt to reclose, and will "lock out" preventing the breaker from being automatically closed again. In this case, a crew is normally dispatched to patrol the line and determine the cause of the fault. Once the issue causing the fault is repaired the line is re-energized manually. Reclosing uses a shot counter to determine the number of times a breaker is reclosed after the initial fault detection. A shot is defined as a cycle where the breaker is tripped open, waits some defined time, and is closed again. Commonly, transmission lines incorporate one or two shots of reclosing to attempt to clear a fault and a distribution line may use up to four shots before locking out. A delay time may be anywhere from a few cycles based on the breakers trip and close speeds up to several seconds depending on the transmission line characteristics as well as environmental factors such as frequency of lightning strikes. Reclosing can be done for all three phases and at higher voltages single-phase reclosing is used to limit the interruption of power flow on all three phases.

Protective relays are devices that measure some quantity, such as voltage or current, and if the relay determines that the measured quantity is abnormal the relay acts to open a circuit breaker to remove the cause of the abnormality. In the past all protective relay were electromechanical, meaning they use electromagnetic forces to rotate a metallic wheel or impart a force on a cantilever beam to cause an electrical contact, or switch, to close resulting in the tripping of a circuit breaker. Creating the logic necessary to implement the protection schemes used often required multiple electromechanical relays, as seen in Figure E-2, each with its own specific

[6] *IEEE Guide for Protective Relay Applications to Transmission Lines*, IEEE Std. C37.113-1999. (1999). New York, NY. IEEE.

function. Still in use today, electromechanical relays are quickly being replaced by more modern solid state and microprocessor based relays. These are based on computer technology and a single relay can be programmed with logic to perform the functions of multiple electromechanical relays. The ability to be programmed means they are more flexible than electromechanical relays, and the use of electronics rather than moving parts results in greater reliability. Because of the much smaller size and complexity of the new relays, it has become standard practice to install a primary relay with a secondary protective relay as back-up to the first in case of failure. Microprocessor based relays are capable of recording pre and post fault data that can help to determine the cause of a fault and if the protection functioned as expected. Modern distance relays can also provide a relatively accurate fault location that will help direct crews appropriately to begin the line inspection. Electromechanical relays do not have these analysis tools.

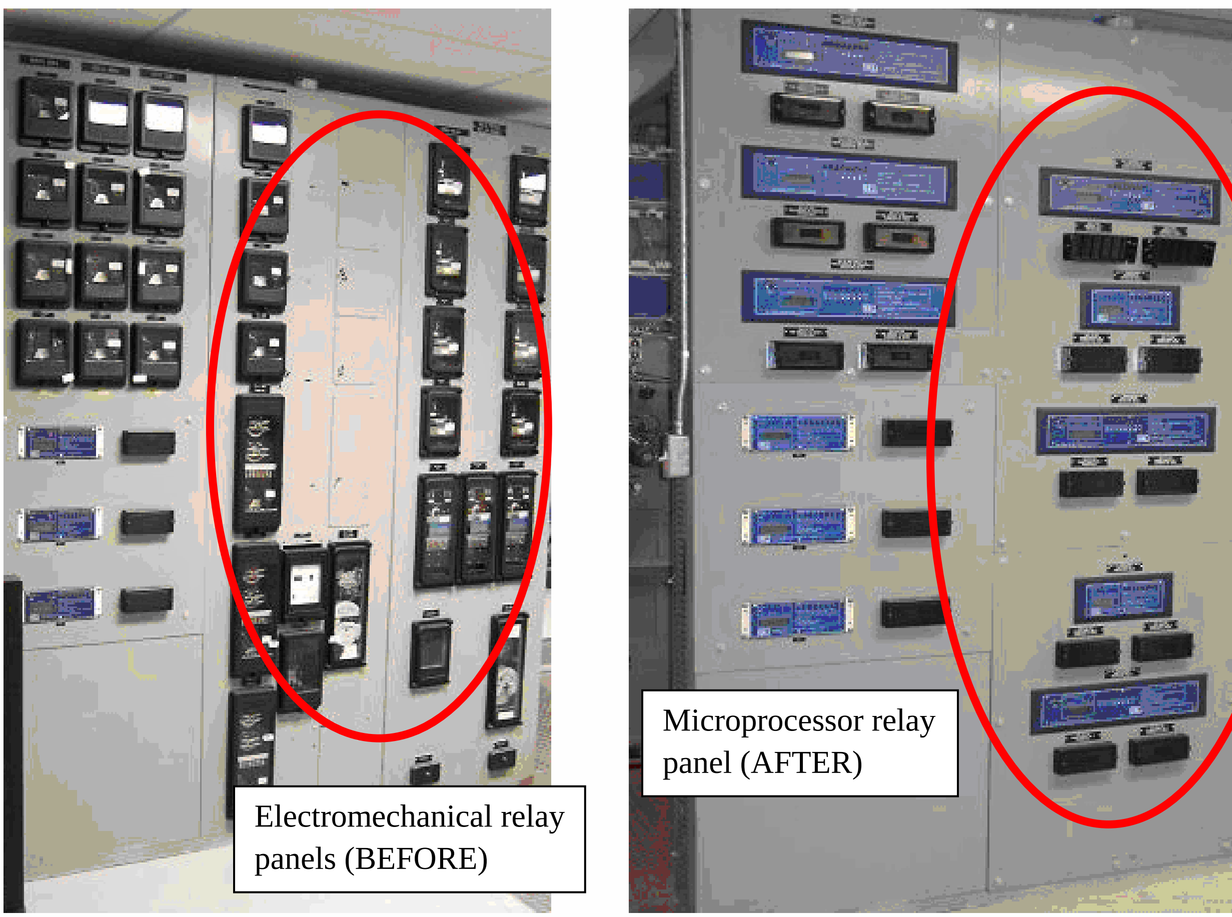

Figure E-2 – The electromechanical relays on left were replaced with the microprocessor based relays on the right. (Photos by NEI)

During the December 2008 ice storm, the causes recorded for transmission line protection operations were documented as being: “trees in line”, “static wire failed and caused fault”, and "no cause found upon inspection". The first two causes resulted in permanent faults. The result was that the breakers protecting these lines tripped and locked out. The "no cause found upon inspection" group was likely due to momentary contact with vegetation or by conductors touching each other due to galloping or line jumping. During these momentary faults, the transmission line protection would have opened breakers to clear the fault and then automatically reclosed the breakers to re-energize the line.

B. DISTRIBUTION SYSTEM PROTECTION

A distribution system is typically a radial system with power lines radiating outward from a single distribution substation. The main power lines normally have multiple taps called laterals which provide power to individual customers. As seen in Figure E-3, a distribution line is similar to a tree in that a main trunk line splits into smaller feeders called laterals that in turn split again to feed individual customers.

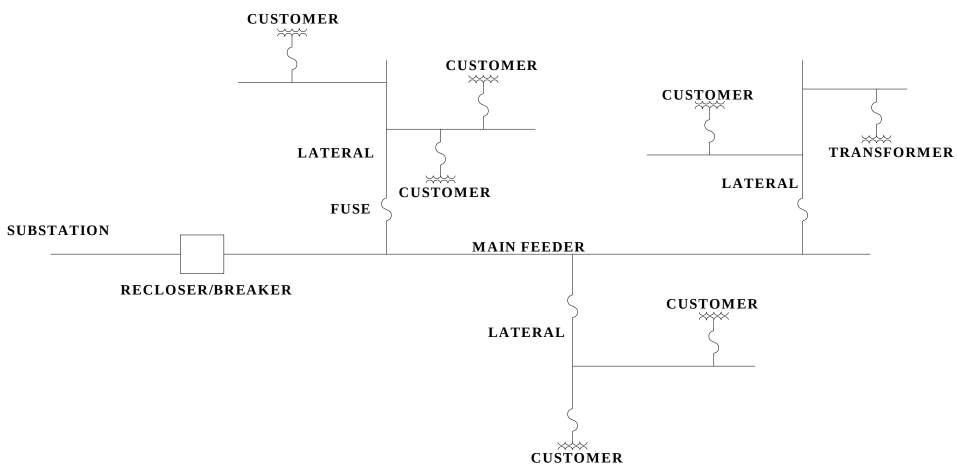

Figure E-3 - Typical radial distribution line[7]

The radial lines may have tie points where they connect to adjacent lines through normally open switches. This allows switching to be done so loads can be fed from more than one line making it possible to take equipment out of service for repair if necessary without interrupting power to customers.

Weather events such as lightning, rain storms, snow storms, or high winds may only affect a small section of the distribution system and likely a single distribution circuit. The distribution system protection will try to react in such a way that temporary faults can be cleared then

[7] *IEEE Guide for Protective Relay Applications to Distribution Lines,* IEEE Std. C37.230-2007. (2007). New York, NY.IEEE.

restored using automatic reclosing. If permanent faults occur, the system protection will attempt to sectionalize the system to keep as many customers with service as possible.

If a fault occurs on a line it can present a hazard to the general public and utility personnel, and may damage other equipment.[8] To disconnect a line where a fault has occurred, a number of devices may be used including circuit breakers, reclosers and fuses. Breakers are typically found in substations and are used in cases where very large fault currents are possible. Breakers will typically have their own current transformers for sensing current, and an external protective relay to monitor current and trip the breaker under abnormal conditions. Reclosers are smaller units allowing them to be mounted on power poles. They act much like a circuit breaker but normally have a lower current interrupting capability. A recloser has its own integral current transformers and is combined with a protective relay that is mounted near the recloser and connected via an umbilical cable. A fuse is the most basic protective element. It is simply an encased metal filament with a known melting point that opens up to disconnect a circuit if too much current passes through it. Fuses are most often used for protecting laterals and taps off of laterals, as well as equipment such as transformers that are connected to laterals.

Faults occur on overhead as well as underground conductors with regularity. They are often caused by weather, equipment failure, vegetation contact, animal contact, and human damage due to digging up cables, vehicle accidents, and vandalism.[9] Fault types that may occur include three-phase, phase-phase, phase-ground, or multiple phases to ground, and protection must be able to sense and properly react to each type of fault. Distribution system protection is predominately over current protection that prevents system components from overloading and damage from short circuit currents.

Sectionalizing and coordination play a vital role in a distribution system's reliability by limiting the number of customers experiencing an outage due to a faulted section of the system. Sectionalizing is the practice of dividing the distribution feeder into smaller sections using devices that can isolate a faulted piece of the system from the remaining system. In order to limit the impact of a faulted section of the system, the standard practice is to use reclosers, fuses, and sectionalizers positioned at strategic locations. Once a distribution feeder has been properly sectionalized to limit wider spread outages, coordination between the sectionalizing devices needs to be developed.

Coordination is accomplished using a concept called inverse time over current (TOC) protection. Any fuse has a known melting time for each level of current flowing through it. If a chart is created showing the time it takes a fuse to melt at each value of current, an inverse time curve is produced as shown in Figure E-4. Electromechanical, solid state, and microprocessor based

[8] *IEEE Guide for Protective Relay Applications to Distribution Lines*, IEEE Std. C37.230-2007. (2007). New York, NY.IEEE.
[9] *IEEE Guide for Protective Relay Applications to Distribution Lin,* IEEE Std. C37.230-2007. (2007). New York, NY.IEEE.

relays emulate this same inverse time characteristic. This allows breakers and reclosers to coordinate with fuses. Relays are set and fuses are chosen so that the protective device closest to any fault opens first, allowing the remainder of the system to stay energized. This process is known as protective device coordination.

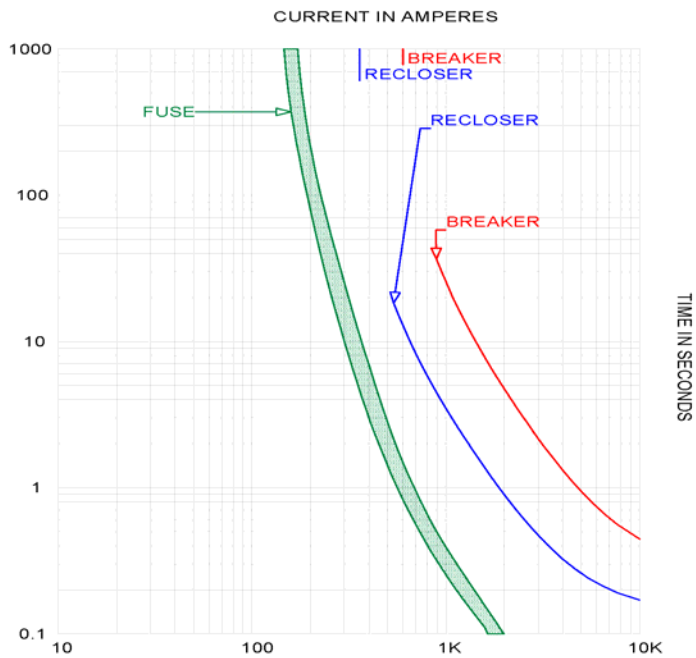

Figure E-4 -Typical inverse time curve for a fuse, circuit breaker, and recloser.

Because most faults are caused by wildlife, wind, and lightning they are temporary in nature.[10] Similar to transmission system protection reclosers or circuit breakers that can be reclosed, are often used to disconnect when a fault occurs and then automatically reclose after a short time. This minimizes the time that customers are without power. Distribution lines may also make use of sectionalizers. A sectionalizer is a device that can disconnect a section of line but is not capable of interrupting fault current. Instead it counts the number of times a recloser disconnects a line by sensing a loss of voltage. If the recloser has tried unsuccessfully to reclose the line a certain number of times, the sectionalizer opens to disconnect a section of line where the fault may have occurred. If the fault occurred on this sectionalized part of the line, the next time the recloser closed it should successfully energize the portion of the line where the fault did not occur. Sectionalizers are an economical means of segregating long distribution lines to limit outages due to faults.

Distribution systems will use one of two protection philosophies when system coordination is planned. Either fuse saving schemes or fuse blowing schemes will be used. A recloser may be programmed to use either a fast operate curve or a slow operate curve. When the recloser opens on its fast operate curve, it will disconnect the line before any fuses on the line have time to blow, saving the fuse. If it operates on its slow curve the fuse will blow first before the line is disconnected by the recloser.

[10] *IEEE Guide for Protective Relay Applications to Distribution Lines*, IEEE Std. C37.230-2007. (2007). New York, NY. IEEE.

If a fuse saving scheme is used, the recloser will be set to use the fast operate curve for one or two attempts, saving the fuse if possible, and then operate on its slow operate curve on its last try to energize the line. If the fault was downstream of the fuse, and was a permanent fault, the fuse will blow before the recloser trips for the final time, allowing power to be restored to the line not affected by the fault. A fuse saving scheme prevents longer outages due to a blown fuse caused by a temporary fault, but may cause more temporary outages to more customers since everyone on the feeder is disconnected instead of just allowing the customers downstream of the fuse to be interrupted.

If a fuse blowing scheme is used, the recloser will always use its slow operating curve. If a fault occurs downstream of a fuse, the fuse will always blow before the recloser opens. This will occur for both temporary and permanent faults. The benefit of this is that only those few customers downstream of the fuse are affected, and most of the customers on the feeder never see their power interrupted. The disadvantage is that the fuse needs to be replaced for all faults, even temporary ones, and the customers being fed through this fuse will be without power until the linemen can drive out to replace the fuse. If the fault was temporary all customers, including those downstream of the fuse, might have been restored after a brief interruption when the recloser opened, if a fuse saving scheme had been used instead of a fuse blowing scheme. Figure E-5 shows typical coordination curves that might be used for fuse saving.

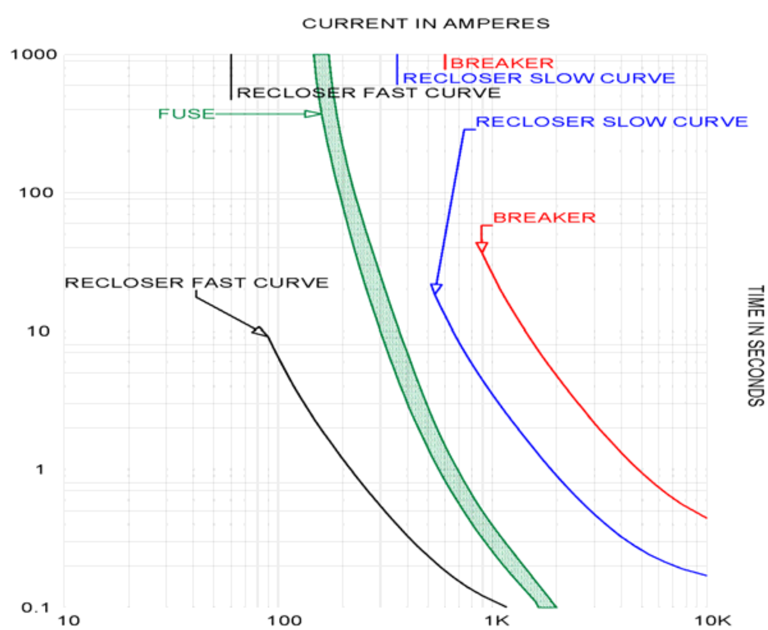

Figure E-5 - Coordination curves for fuse saving.

During the early stages of the December 2008 ice storm, the distribution system functioned as would normally be expected by isolating sections of the system with permanent faults and restoring power to sections affected by temporary faults. As the storm worsened and tree limbs began to break and entire trees began to fall into the distribution lines, the distribution line protection at the substations began to lock out due to the permanent nature of the faults.

C. SUBSTATION PROTECTION

The type of protection used in a substation is often determined by the size and importance of the substation. Normally higher voltage substations with larger transformer sizes require more intricate protection schemes whereas smaller substations may require only minimal protection.

Substation protection schemes are designed to protect the equipment in the substation, the lines supplying the substation's power, and the lines leaving the substation. In most cases, a breaker or circuit switcher is used as the main protective device on the high voltage side of the substation transformer.

Transmission substations have three zones of protection, each utilizing different protection methods (Figure E-6).[11] The first zone is the incoming bus or high voltage bus. The second zone is the transformer zone and the third zone is the feeder bus or low voltage bus. There are several ways to protect the high voltage bus, and the method used is based on the substation configuration. The high voltage bus may be protected by the same relays protecting the transmission line, or it may be protected with a current differential relay that compares current flowing into the bus with that flowing out of the bus. Transformer protection is usually provided by a transformer differential relay that compares the current flowing into the high voltage side of the transformer with that exiting the low voltage side. An over current relay located on the high voltage side of the transformer may also be used to protect the transformer. The low voltage bus may be protected with a differential relay or may simply be protected with an over current relay. The lower voltage lines leaving the substation are each protected using breakers and either overcurrent or distance relaying. Often, automatic reclosing is used on the outgoing lines.

[11] Blackburn, J.L. (1987). *Protective Relaying, Principles and Applications*, 2nd Ed. New York, NY. Marcel Dekker. pg. 28.

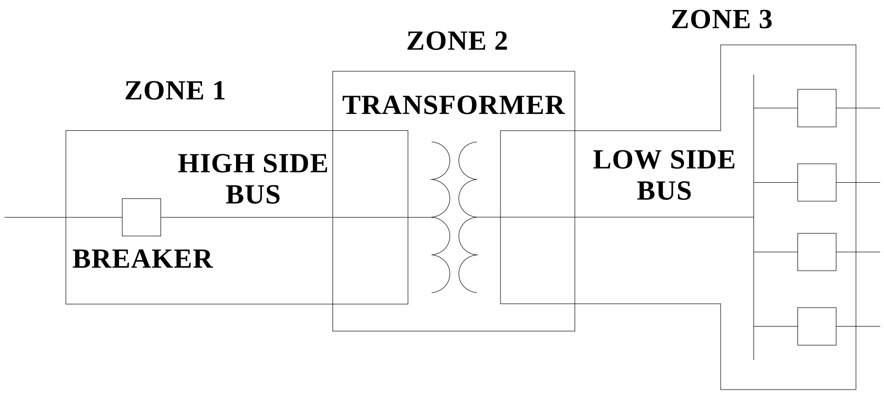

Figure E-6 – Substation protection zones.

Distribution substations are often smaller physically and use a smaller transformer than transmission substations. Protection schemes used in larger distribution substations or substations deemed critical are similar to the schemes used in transmission substations. Smaller distribution substations may simply have a high side fuse protecting the high voltage bus, transformer, and low voltage bus. Reclosers are often used for outgoing feeder protection.

Substation protection is designed to limit the damage that can occur to the equipment located in the substation including the transformer, breakers, reclosers, and buses. It may often be expensive and time consuming to repair or replace equipment in a substation. This means it is very important to limit damage to substation equipment whenever possible. If faults occurring on the electrical system outside of the substation are not quickly removed, they may cause damage to the equipment inside the substation.

In most cases during the December 2008 ice storm, the substation protection used by the New Hampshire utilities worked effectively to prevent damage to critical equipment and disconnect damaged feeders as necessary. Only one protection related failure occurred when a wye-delta-wye power transformer failed due to inadequate protection.