Wildfire Protection Strategies for Overhead Bare Wire Power Systems

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1. INTRODUCTION AND BACKGROUND

Overview

The potential for electric overhead power lines to provide an ignition source for wildfires has prompted utilities to change long held protection strategies that were implemented to minimize outages and implement strategies that focus on ignition prevention. In extreme conditions, the need for prevention may even justify deenergizing the system until the extreme conditions decrease. While there are many asset-based investments such as undergrounding or installing covered conductors to reduce wildfire ignitions, changing protection strategies can also reduce ignition risks. When considering enhanced protection strategies for high fire threat areas, it is important to consider historical fault causes and ignition incidents for circuits in that area and develop an ignition mitigation strategy that considers the options presented in the summary table at the end of this document.

Reclosing

Traditional reclosing builds on the assumption that the high-current fault may be temporary in nature and that a “reclose” may have the ability to reenergize customers with just a few or none of the customers experiencing a sustained outage. During wildfire conditions, traditional reclosing is disabled since the potential to create an ignition increases with each subsequent reenergization. For example, a tree falling into a line that pushes the conductors together as it falls will create a conductor-to-conductor fault in the air that is quickly deenergized by overcurrent protection devices. While there is the potential for the tree to be ignited by the arc, the potential for an ignition is much greater if the conductors are reenergized under the tree at ground level in direct contact with dry ground cover that is readily combustible. Since the reliability benefits of traditional reclosing can be closely matched by intelligent reclosing and fast dispatch, the disabling of traditional reclosing is assumed for the remainder of this paper when wildfire risk are elevated.

Understanding Ignition Faults

Bare electric lines can cause ignitions in several ways. This paper will attempt to offer protection strategies for each type of ignition. Understanding how the fault occurs is the key to making sure the most probable fault types and their impacts on ignition are mitigated. Mitigation is different than prevention as some ignitions will not be preventable. Ignitions that cannot be prevented will depend on detection and locational tools to enable quick dispatch.

Ignition Faults Caused by High-Current Electrical Faults

For some faults, it is the high electrical current associated with the fault that provides the energy to create an ignition. These high-current events can easily be detected and interrupted by conventional protection relays and fuses. The main concern with these faults is that the fault current, which is interrupted, may have also created an ignition.

There are a few primary examples of this type of fault. The first is a mylar balloon (or some other highly conductive material encroaching the lines). Mylar balloons have a conductive surface that creates a high-current arc across the balloon when the balloon contacts two conductors. When the arc occurs, the balloon may ignite from the arc energy which could lead to fire droplets that can ignite other objects. The second example is a conductor contacting another conductor. When conductors touch, as shown in Figure 1, the resulting arc is very hot and will melt some of the conductor. Both the arc and the bits of melted conductor pose an ignition risk. Conductor touching can be caused by several events such as a car hitting a pole, a tree falling against a line pushing conductors together, conductors blown together by wind, or conductors slapping from magnetic forces associated with another fault. Since all conductor-to-conductor faults exhibit the same fault signature and pose the same ignition risk, they will be treated the same. Another low impedance / high current fault could be wildlife contacts between conductors or between conductors and grounded equipment.

Figure 1. *Arc and molten metal from conductor slap*

Mitigation

Mitigation efforts for ignitions caused by the fault energy follow a set process:

- Relatively fast clearing
  - "Relatively" means as fast as possible while still maintaining some level of coordination with other protective devices on the circuit.
    - Coordinating with tap fuses requires a time current curve that enables the energy within the arc to be multiple times greater than the energy in an arc cleared by extremely fast procedures.
  - Extremely fast clearing is also an option but will not allow for time needed to calculate the approximate location based upon fault targets or fuse operations.
    - Extremely fast clearing can be accomplished by current-limiting fuses.
    - Not coordinating with fuses requires inspections to include areas behind fuses.
- Fast locating
  - By maintaining coordination, the location of the fault can be quickly identified for immediate dispatch. The location of the fault is generally identified by fault targets or a protective fuse blowing.
  - The low-impedance nature of these faults means that line impedance is the primary throttle to the fault magnitude. This relationship enables the use of fault magnitudes to be matched to the system impedance that would support the magnitude. Impedance matching enables a very close determination of the location of the contact.
- Fast dispatching
  - Fast dispatching is a critical step in the mitigation process. These types of faults may have already created the ignition. While the probability of ignition is lessened by the relatively fast clearing, the probability still exists and quick inspection of the fault is beneficial.
  - A complete inspection of all faults is also important to ensure that any damage to the conductor is repaired. A damaged conductor that is not repaired is prone to future failure without an associated fault event.

Ignition Faults Caused by Low-Current Electrical Faults

Low-current faults pose a significant challenge for traditional protection relays. The low current associated with these faults appears as load to protective relays and fuses. When semiconductive foreign material is between conductors, the conductive characteristic of the material forms a low-current path. Unless the material is a true insulator, over time the material will begin to break down into different chemical elements. Depending upon the material, the material may sit on the line for a few minutes to days or longer before enough chemical change and gas creation occurs to provide a low-impedance current path between the conductors resulting in a high-current fault that is detected by traditional protection relays.

Low-current material between conductors

When a semiconductive material is suspended between conductors, the material breakdown continues until either the breakdown reaches across the entire material resulting in a high-current fault or until the material is mechanically weakened enough to break and fall to the ground. Ideally, for wildfire prevention, it would be preferable to keep the material in the air until a first responder can arrive and remove the material before it falls. However, some items will burn until structural integrity is weakened to the point of failure resulting in the charred material falling to the ground. Other instances may damage the conductor at the point of material contact resulting in the conductor being damaged enough to break apart and fall to the ground. The contributing factors to conductor breakage are not completely understood but could include wire size, material weight, material density, and line tension.

Figure 2. *Active conductor to pole contact*

Examples of these types of faults, shown in Figure 3, Figure 4, and Figure 5, include:

- Vegetation laying across phases or between a phase and neutral
- Vegetation, such as bamboo, that grows quickly between the neutral and a phase conductor
- Conductors touching a pole or a wood crossarm
- Equipment failure

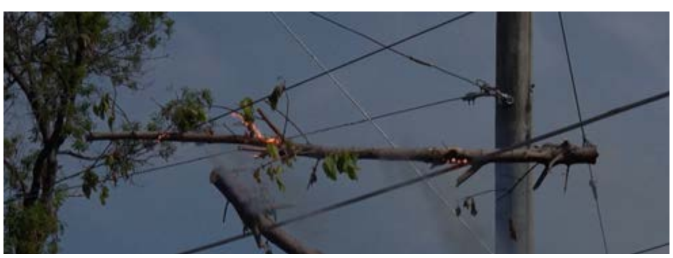

Figure 3. *Limb across 12 kV conductors charring on the way to becoming a fault*

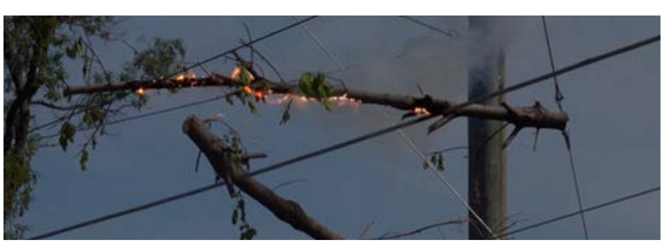

Figure 4. *Limb across 12 kV conductors just prior to becoming a high-current fault*

Figure 5. *Limb across 12 kV conductors developing into a high-current fault*

Low-current material between a conductor and ground without direct neutral involvement

When the current path for a fault includes the earth, the current path is very inconsistent and is based upon the material on which the conductor rests, the resistivity of the soil, and the distance the current must travel through the soil before returning to a conductor-based neutral. Rarely do these events have enough fault current to activate overcurrent protection relays or fuses. A bare conductor on wet grass, for example, may conduct tens of amps that can be detected by arc-sensing relays. However, most occurrences with conductors on bare soil or asphalt conduct very low fault currents that will not be detected by a current-based protection device. Conductors that contact the ground energized by an associated conductor breakage can be detected by advanced metering infrastructure (AMI) outage patterns or loss of voltage protection systems.

Examples of faults that include an earth return path include the following:

- Vegetation growing in from the side and only touching one phase
  - The path is through the vegetation then through the ground as the fault seeks a return path to the substation. Such fault currents are low and generally undetectable.
- A conductor that breaks without a high-current fault and remains energized when it reaches the ground
  - The breakage could be the result of a limb across phases, a previously damaged conductor failing, or a splice failure.
  - The path is through the ground as it seeks a return path to the substation.

Mitigation – vegetation

Material that is charred and never progresses to a high-current fault or breaks the conductor is generally not detectable. An example may include a tree leaning into or growing into a single-phase conductor. Another example is a limb that breaks from the charring and falls to the ground before creating a high-current arc. The primary mitigation for these events revolves around vegetation management strategies. The act of removing canopies over the distribution line is an example of a preventive strategy for these types of faults.

Mitigation – conductor breakage

Conductors that break, for whatever reason, are not identified by current-based protective devices unless the broken conductor contacts another conductor as it falls or if it falls on a semiconductive material that supports an arc that can be detected by arc-sensing relays. The two primary technologies for identifying broken conductors are communication-based voltage sensing and the use of AMI outage reporting. Both technologies will be discussed in greater detail in a subsequent section. The use of AMI outage messages is an example of fast locating as the AMI patterns identify the location of the break. The use of voltage sensing at line end attempts to deenergize an impacted line before it reaches the ground.

2. RELATIVELY FAST COORDINATION

Overview

Since there are known instances where charring of the material occurs prior to the development of a high-current fault, quickly locating the fault location so that a physical inspection can occur is an important step to reduce the chances of an ignition incident becoming a wildfire. If the number of events occurring exceeds the quick inspection capabilities of first responders, a public power safety shutoff could be warranted.

Maintaining coordination of protective devices can dramatically shrink the area of dispatch to a small protection zone. However, unlike traditional coordination that relies on extending protection delays, relatively fast coordination programs all involve non-fuse protection devices to operate on the same relatively fast delay curve. This delay curve is chosen to traditionally coordinate with a particular fuse size. For example, the decision may be to have all fuses capped at 65 K, and the protective devices would be programmed to coordinate with all fuses 65 K or smaller.

Series Protective Devices with Identical Protection Curves

Placing protective devices in series is an effective strategy to isolate a fault to a zone of customers. Some utilities with aggressive recloser placement programs have zones with as few as 250 customers in each one. Programing the protective devices and the feeder breaker with the identical protection curves eliminates the need for long clearing times or coordination of reclosing intervals. Coordination is performed through a logical evaluation of fault targets. In the example shown in Figure 6, all the devices will be programmed with identical protection curves that are delayed just enough to coordinate with the maximum fuse size.

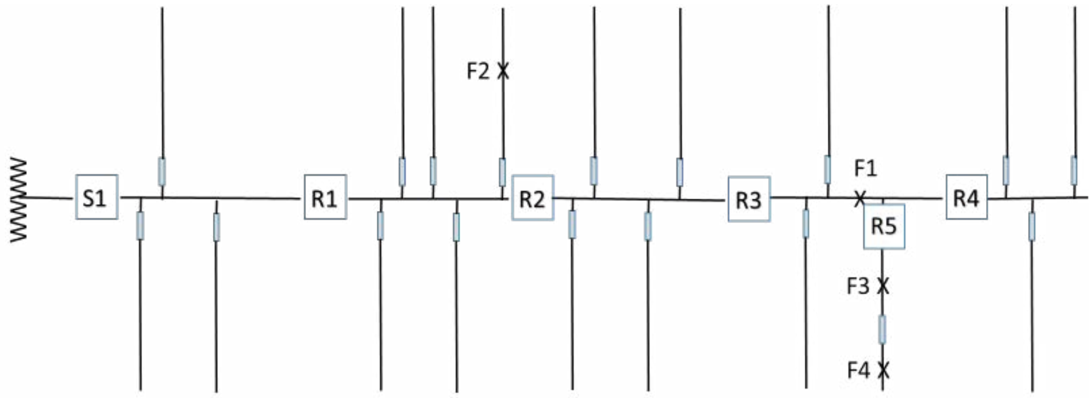

Figure 6. *Example feeder with series reclosers*

- For a fault at location F1, the S1, R1, R2, and R3 series reclosers all open with the same targets. Either automated fault location, isolation, and service restoration (FLISR)-based logic or the operator evaluates the targets and employs supervisory control and data acquisition (SCADA) system commands to close S1, R1, and R2. The FLISR system or operator may also open R4 and energize from an alternate source. The area known to have a fault (between R3, R4, and R5) is not reenergized until an inspection is performed. The inspection would not need to involve the line behind fuses or behind closed lateral reclosers.
- For a fault at location F2, series reclosers S1 and R1 assert on their protection curves, but the fault is cleared by the protection fuse prior to either device opening. The fuse outage is dispatched for a fast inspection.
- For a fault at location F3, series reclosers S1, R1, R2, R3, and R5 all open with the same targets. Either automated FLISR-based logic or the operator evaluates the targets and utilizes SCADA commands to close S1, R1, and R2. Closing of R3 will be based upon the type of lateral recloser being used. If R5 is a SCADA-enabled recloser that reports status and targets, R3 would be closed. If R5 is a cutout mounted recloser or hydraulic recloser programmed for a single operation, a status sensor system may be required. Similar to fault 1, an alternate source may be used to energize behind R4.
- For a fault at location F4, series reclosers S1, R1, R2, R3, and R5 all assert on their protection curves. The fault, however, is cleared by a fuse before any series reclosers open. The fuse outage is dispatched for a fast inspection.

3. FAST LOCATION IDENTIFICATION

AMI for Fast Fuse Outage Detection

AMI meters report outages based upon an outage timer. Extended outage timers can be used to filter momentary outages within the meter. For example, a meter may have an outage timer of 30 s. With a 30 s outage timer, an outage event that is restored with reclosing within 30 s does not create an outage notification. For some utilities, the outage timer is less than their reclose cycle. When the outage timer is less than the reclose cycle, utilities are forced to filter outages from the AMI system to prevent false predictions within the outage management system (OMS).

When reclosing is disabled, the filtering of AMI outages is no longer required. When filtering is removed, the AMI outage messages can be quickly ingested into the OMS creating near real-time outage predictions. AMI systems without extended outage timers may report outages within a few seconds. AMI systems with extended outage timers will report within a few seconds after their outage timer expires. This is especially important in quickly dispatching crews to isolated faults behind fuses. Along with very fast outage predictions, the visualization of the outage messages can also be used to identify the location of broken conductors that have remained energized.

Vibration Sensors for Hydraulic and Cutout Mounted Reclosers

When reclosers are deployed in series with the same protection curves, AMI or customer calls cannot be used to indicate a non-SCADA device has opened. Vibration sensors mounted on the pole may offer an effective way to determine if the non-SCADA device has operated. The sensitivity of these devices is such that false indications may occur. However, since a true operation will always also involve upstream recloser(s), the sensors are only evaluated when all upstream devices operate.

Fault Magnitude Impedance Matching

Most faults have a relatively low impedance at the fault location. For example, a high impedance limb becomes a low impedance arc when the limb turns to carbon and gasses that readily conduct electricity. Since the fault material becomes conductive, the magnitude of current within the arc is primarily determined by the impedance of the distribution system. Distribution system models can accurately calculate the system impedance at any location. The two variables, fault magnitude and system impedance, can be combined to identify the location of a fault to within a few spans. Data that impact the accuracy include the following:

- Substation transformer impedance
- Correct wire size within the model
- Consistent conductor spacing within designs
- Distribution sited generation that materially contributes to the fault current

The fault current magnitude can be captured at any point along the feeder. A common collection method is to have the fault magnitude reported from the substation breaker anytime the relay asserts on its protection curves. By not requiring the relay to open, this method reports fault magnitude behind all protective devices on the feeder, including the protective device that isolated the fault. The fault magnitude can be impedance matched to probable locations behind either the logical recloser or the fuse indicated open within the OMS. The fault magnitude does not have to be wave form data. Successful location identification has been consistently achieved with a single magnitude value accompanied by the phases involved with all the data provided by the protection relay through SCADA communication paths.

Impedance matching has also proven very effective in locating temporary faults such as those caused by wind-induced conductor-to-conductor faults.

4. CONDUCTOR BREAKAGE IDENTIFICATION

Overview

When conductors break without an associated fault, the events pose a problem for traditional current-based detection methods. A few detection technologies are designed to quickly identify the condition of a broken energized conductor. Since these events do not have an associated fault operation, they are not prevented by disabling reclosing. Primary examples include wire burn down from vegetation faults, splice mechanical failure, and the mechanical failure of conductors previously damaged from a high-current fault. Previously damaged conductors are lessened if each fault occurrence is located and inspected using location technology.

Voltage Monitoring Technologies

When a conductor breaks, the voltage beyond the break is impacted. By monitoring the voltage at endpoints, the identification of a break can be utilized to initiate an opening of protection devices ahead of the conductor break.

Communication-based loss of voltage

One option is to utilize communication between circuit endpoints and upstream protective devices, as shown in Figure 7. When the endpoint device senses a loss of voltage, a message is sent to the upstream protective device. If the protective device (R3) is open, the process stops. If the protective device is also sensing a source side voltage loss, the message continues upstream. Eventually, the message reaches R1, which does not have a loss of source side voltage. If R1 is open, the process ends. If R1 is closed, it will immediately open. These communication systems have been shown to deenergize conductors before the conductor hits the ground (less than 1500 ms). These systems can also work with devices programmed to trip phases independently.

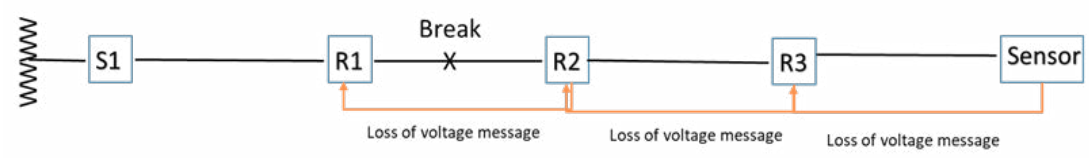

Figure 7. *Communication between circuit endpoints and upstream protective devices*

SCADA-based loss of voltage

While not fast enough to trip an upstream protective device before a broken conductor reaches the ground, SCADA devices can be programmed to alarm for loss of voltage. Loss of voltage alarms are generally regarded as nuisance alarms since their presentation usually does not convey any new information to the operator. However, some alarm designs eliminate nuisance alarms while bringing priority alarms forward for review.

If all the devices trip all three phases, then all devices can have an alarm programmed in the protective device's control to create a priority one alarm anytime a loss of voltage only occurs on one or two phases. Loss of voltage on all three phases would not create any alarm. This system works with or without reclosing enabled.

If the devices have single phase trip enabled, the logic becomes much more complicated as each phase must be reviewed independently. The normally open device creates a status point for the loss of Phase A. When the loss of phase A status point asserts, it is compared to the status of phase A on S1, R1, R2, and R3. If none of the devices indicate an open phase A device, a priority alarm is created, as shown in Figure 8.

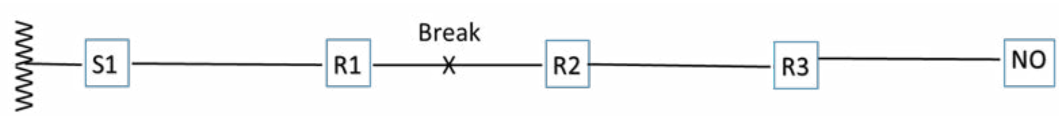

Figure 8. *Creation of a priority alarm (NO = normally open)*

Grounding-based loss of phase

Another option for fast mainline conductor break detection involves an end-of-line sensor coupled with a three-phase grounding device. Unlike the communication-based system, the grounding-based system requires that all the upstream protective devices trip in a three-phase ganged operation, as shown in Figure 9. The logic works as follows.

1. The normally open ground device senses a loss of one or two phases.
2. All the protective devices have an alarm when they sense the loss of voltage on one or two phases only.
3. The grounding device closes, placing a three-phase fault on the line.
4. All the inline protective devices open, including the substation breaker.
5. This loss of voltage alarms (on protective devices R2 and R3) inform the operator of the break protection zone.
6. The ground switch can be programmed to automatically open or remain closed until the broken conductor is isolated.

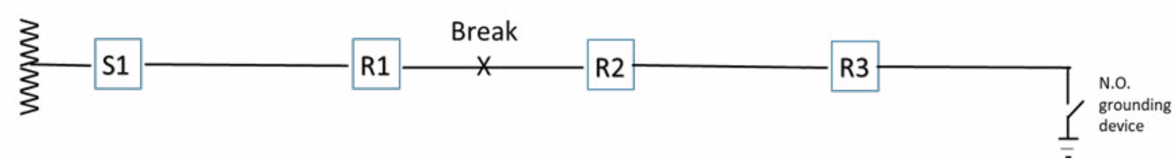

Figure 9. *Grounding device at the end of the feeder*

- A general assumption is that is takes about 2 s for a conductor to fall to the ground. When determining if a system is capable of deenergizing the conductor before it contacts the ground, the total time from the break to isolation should be under 1500 ms. The following sequence of events must be added together to determine if 1500 ms isolation is achieved for a broken conductor without a fault event.
- Duration of loss of voltage at the ground device to trigger an event of 42 cycles is 700 ms.
  - The same time is set in R1, R2, and R3 to create a loss of voltage alarm.
    - Only R2 and R3 would have the loss of voltage alarm.
- Time for the ground device to close is 60 ms.
- All upstream protective devices trips are based upon a time-current curve of 600 ms.
  - All protective devices would have a phase-to-phase fault target.
    - R2 and R3 would have a loss of voltage alarm.
- Total time from open phase to isolation is 1360 ms.

Care should be taken to make sure the ground device does not operate quicker than the recloser protection curve. This may entail a longer delay than 700 ms. If the grounding switch is closed before a recloser has time to trip for a phase-to-ground fault, the logic to identify the location of the fault through the evaluation of targets will be defeated. For example, if the break in Figure 9 is replaced with a phase-to-ground fault and the loss of voltage trigger is set too short, the following sequence may occur:

1. A phase-to-ground fault occurs between R1 and R2 that lowers the voltage beyond it.
2. S1 and R1 assert for a phase-to-ground fault.
3. R2 and R3 assert on a loss of phase voltage.
4. Grounding device asserts for a loss of phase voltage.
5. Grounding device closes for loss of voltage.
6. S1, R1, R2, and R3 now assert for a three-phase fault.
7. S1, R1, R2, and R3 open with three-phase targets.

The scenario above would be confusing to automated FLISR logic or to operators. With a delay on the ground device to allow all reclosers to operate, only S1 and R1 would open with phase-to-ground targets. R2 and R3 may exhibit a loss of voltage alarm but would remain closed without any fault targets, as shown in Figure 10.

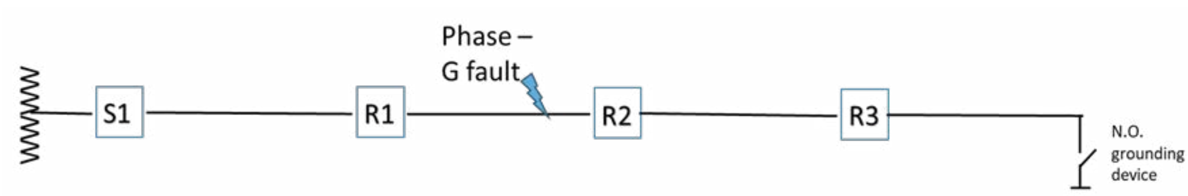

Figure 10. *Feeder with a phase- to-ground fault*

Use of AMI Without Traditional Reclosing

As mentioned earlier, the time delays associated with AMI outage filtering can be eliminated when reclosing is disabled. The elimination of filtering delays allows AMI outage messages to quickly create an outage prediction for fuses. When an outage behind a fuse occurs, the operator can view the AMI messages in the OMS map to determine if the pattern of a down conductor exists (most OMS systems have the capability to visualize AMI outage messages). Down conductors exhibit the pattern of customers without an outage followed by customers beyond the break with an outage, as shown in Figure 11. The point at which outages start occurring is the location of the conductor break.

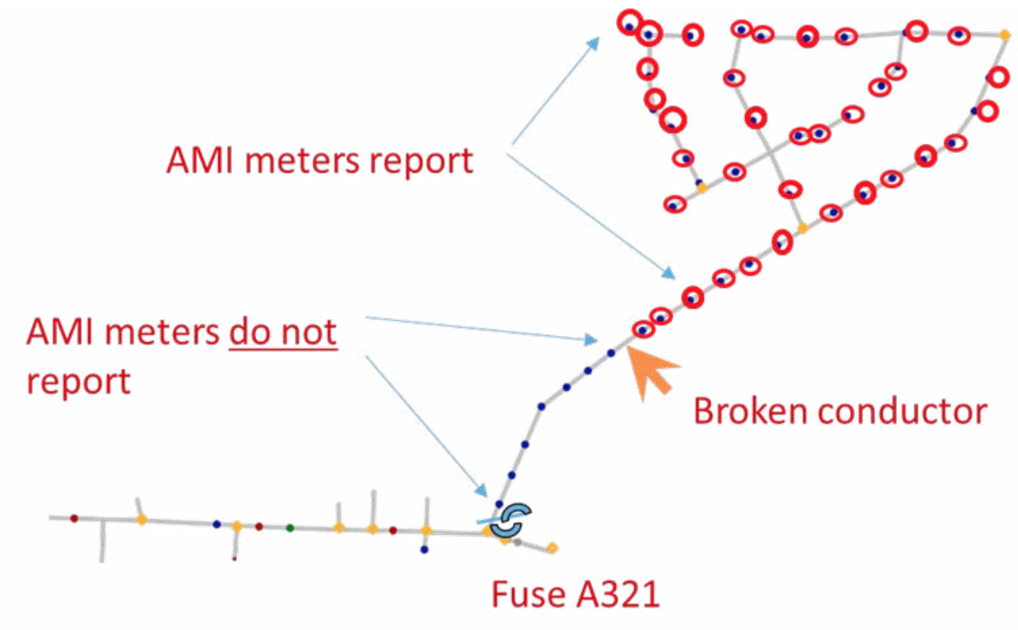

Figure 11. *AMI outage pattern of a broken conductor*

The same process will work for reclosers. When all reclosers are programmed with the same protection curves, a fault condition behind a recloser will lock out all reclosers. However, when a conductor break occurs without a fault, the AMI outages behind the conductor break will be analyzed by the OMS resulting in an outage prediction associated with the closest protective device. Since recloser predictions should not be occurring (assuming that at least the breaker has SCADA), the operator should make note of the location where the AMI outage messages indicate the conductor is broken and then open the recloser predicted by the OMS. If the recloser is a lateral recloser without SCADA, the operator should open a SCADA device serving the lateral recloser. After deenergizing the line, first responders should be dispatched to the location identified by the AMI outages.

5. ARC ENERGY LIMITING

While many fault types are already ignited or at least charred before a high-current fault occurs, as seen in Figure 4, there may still be a desire to limit the fault energy to lessen the probability of an ignition caused by the fault current. This process is especially effective if there is a desire to prevent expulsion fuses from operating during the wildfire conditions. Expulsion fuses disperse molten materials toward the ground when they operate. There is concern that the molten material emitted by the fuse may start a fire at the base of the pole where the fuse is mounted. Depending upon the size of the fuses deployed and the available fault current, expulsion fuses may still operate with instantaneous settings placed in protective devices. One mitigation option is to replace traditional expulsion fuses with non-expulsion fuse designs. A different philosophy is to prevent existing expulsion fuses from operating when wildfire conditions exceed a specific rating by installing current-limiting fuses.

Current-Limiting Fuses/Electronics

Current-limiting fuses are different than expulsion fuses in that they are completely sealed and have the unique design that increases the arc voltage as the fuse interrupts the current. This drives the arc voltage above the system voltage and extinguishes the fault within one-half cycle, as shown by the examples in Figure 12 and Figure 13. This action not only interrupts the fault current but also limits the magnitude of current passing through the fuse. By inserting a current-limiting fuse in series with other protection devices, the current-limiting fuse will reduce the arc energy at the fault location by limiting the magnitude of the arc and the time it is present. If sized properly, the current-limiting fuse will also be faster than traditional expulsion fuses and prevent them from operating.

Figure 12. *Fuse operating to clear an arc across a mylar balloon*

Figure 13. *Fuse fireball attempting to ignite shredded wood fibers*

Care must be taken when specifying the current-limiting fuse utilized as the fuse can be damaged by currents above their constant current rating but below their minimum interrupting rating. For example, if the current rating of the fuse is exceeded by in-rush current, the fuse will begin to break down from the heat created. During wildfire conditions, the removal of reclosing also eliminates in-rush currents associated with the reclosing action. The removal of in-rush conditions may allow the current-limiting fuses to be sized closer to the load rating than if reclosing were common. To prevent in-rush conditions, the design of the current-limiting fuse installation can allow it to be placed into service by closing the fuse in parallel with a closed device. The closed device is then opened to place the fuse completely in service. The same device is then used to bypass the current-limiting fuse when the fuse is removed from service.

Since current-limiting fuses will not coordinate with other protective devices – and the current-limiting fuse alters the fault magnitude so that impedance matching cannot be utilized to help identify the location of the fault – inspections must be performed on the entire feeder behind the current-limiting fuse. This requirement may limit the ability to quickly dispatch someone to the fault location. There is some thought that electronic protective devices and fault indicators could be programmed to target for the fast reduced magnitude fault current passing through its location. If targeting is enabled, the patrol area could be reduced to specific zones determined through analysis of the fault targets.

Summary

Table 1 identifies some common ignitions and detection methods, whether protective coordination is maintained, and mitigation practices.

Table 1. *Common ignitions, detection methods, and mitigation practices*

IGNITION	DETECTION	PROTECTIVE COORDINATION	MITIGATION PRACTICES
Mylar Balloon	Protective device	No	Current-limiting fuse to limit ignition energy
Mylar Balloon	Protective device	Yes	Fast dispatch to area based upon targets, outages, and fault magnitude
Vegetation that burns and drops without a fault	None	N/A	Vegetation management
Vegetation that creates a fault	Protective device	Yes	Fast dispatch to area based upon targets, outages, and fault magnitude
Conductor break	Communication-based voltage monitoring	N/A	Protective device trip prior to reaching the ground
Conductor break	Voltage monitoring with grounding	No	Protective device trip prior to reaching the ground
Conductor break	SCADA monitoring	Yes	Protective device trip after the conductor hits the ground and fast dispatching based on protection zone
Conductor break	AMI	Yes	Fast dispatch with AMI location
Fault-induced conductor slap	Protective device	Yes	Relatively fast clearing does not support conductor movement
Wind-induced conductor slap	Protective device	No	Energy limiting by current-limiting fuse
Wind-induced conductor slap	Protective device	Yes	Fast dispatch based upon protective zone and fault magnitude
Expulsion fuse	Protective device	Yes	Replace expulsion fuses with fuses that capture and contain all molten material
Expulsion fuse	Protective device	No	Prevent fuse operation by instantaneous trip or current-limiting fuses

6. REFERENCES

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